Modelado de la vida útil de piña (*Ananas comosus*) mínimamente procesada empacada en atmósferas modificadas a partir de propiedades indicativas de calidad y condiciones de almacenamiento

José Miguel Gómez Moreno

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Facultad de Ciencias Agrarias

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Director:

Dr. Aníbal Orlando Herrera Arévalo

Codirector:

Dr. Diego Alberto Castellanos Espinosa

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Modeling shelf life of minimally processed pineapple (*Ananas comosus*) in modified atmosphere packaging from quality-indicative properties and storage conditions

José Miguel Gómez Moreno

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Co advisor:

Dr. Diego Alberto Castellanos Espinosa

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Dedicatoria

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Resumen

Esta tesis presenta un modelo para predecir la vida útil de piña mínimamente procesada a partir de las propiedades indicativas de calidad como función de la temperatura y la concentración de gases en un sistema de empaque con atmosferas modificadas (MAP). Para esto, primero se desarrolla un modelo matemático para describir las velocidades de respiración (consumo de O_2 y producción de CO_2) y de transpiración de la piña procesada mínimamente (cortada en rodajas) en función de la temperatura, la humedad relativa (HR) y la configuración geométrica. Para ajustar experimentalmente los modelos adecuados para la respiración y la transpiración, la piña (*Ananas comosus*) mínimamente procesada se almacenó en rebanadas de tres tipos de configuración (media rodaja con 1 cm de espesor, una rodaja completa con 1 cm de espesor y una rodaja completa con 2 cm de espesor) a diferentes temperaturas y HR. El consumo de O_2 y la producción de CO_2 se modelaron utilizando una cinética enzimática de Michaelis-Menten. A lo largo de los diferentes experimentos, las velocidades de respiración fueron mayores al aumentar la temperatura de almacenamiento. Los datos de transpiración muestran que la pérdida de peso es lineal para todas las muestras durante todo el tiempo de almacenamiento. Los resultados muestran una alta bondad de ajuste entre los datos experimentales y los valores estimados con los modelos de respiración-transpiración (R^2> 0,89). En segundo lugar, las rodajas completas de piña mínimamente procesada con 1 cm de espesor se almacenaron a diferentes temperaturas y concentraciones de gases para determinar los cambios de firmeza, color y otras propiedades fisicoquímicas a través del tiempo de almacenamiento con el objetivo de representar la vida útil en función de la temperatura y concentraciones de gases a partir de estas propiedades de calidad. A partir de los datos experimentales, los modelos se ajustaron adecuadamente para representar el cambio de cada una de estas propiedades en función de la temperatura y las concentraciones de gases mediante el uso de un modelo de potencia para la firmeza y un modelo de primer orden para representar el color (coordenadas L*, a* y b*). Desde el modelo de firmeza fue posible obtener una ecuación adecuada para predecir la vida útil de la piña mínimamente procesada a partir del almacenamiento de temperatura y concentración de gases, obteniendo coeficientes de regresión superiores a 0.90. Con el modelo de vida útil desarrollado en este estudio es posible configurar condiciones de empaque adecuadas dependiendo de las necesidades específicas del mercado a lo largo de la cadena logística y de distribución.

Palabras clave: piña, empacado en atmosferas modificadas, propiedades de calidad, modelado, vida útil

Abstract

This thesis presents a model to describe the shelf life of minimally processed pineapple depending on quality-indicative properties and as a function of the temperature and gas concentration in an equilibrium modified atmosphere packaging (EMAP) system. For that, a mathematical model was first adjusted to describe respiration (O_2 consumption and CO_2 production) and transpiration rates of minimally processed pineapple (cut into slices) as a function of temperature, relative humidity (RH) and geometric configuration. To experimentally adjust suitable models for respiration and transpiration, minimally processed pineapple (*Ananas comosus*) was stored in slices of three types of configuration (a half slice with 1 cm of thickness, a complete slice with 1 cm of thickness and a complete slice with 2 cm of thickness) at different temperature and RH. The O_2 consumption and CO_2 production were modeled by using a Michaelis-Menten enzyme kinetics. Throughout the different experiments, the respiration rates were higher by increasing the storage temperature. The transpiration data showed the weight loss is linear for all the samples during the entire storage time. Results shows a high goodness of fit between experimental data and estimated values with the respiration-transpiration models (R^2 > 0.89). Secondly, minimally processed pineapple (*Ananas comosus*) slices with 1 cm of thickness were stored at different temperatures and gas concentrations to determine the changes of firmness, color and other physicochemical properties through the storage time with the aim to represent the shelf life depending on temperature and gas concentrations from these quality properties. From the experimental data, models were adequately adjusted to represent the change of each one of these properties as a function of the temperature and gas concentrations by using a power model for the firmness and a first-order model to represent the color (L*, a* and b* coordinates). From the model of firmness was possible to obtain a suitable equation to predict the shelf life of the minimally processed pineapple from the temperature and gas concentration storage, obtaining regression coefficients higher than 0.90. With the shelf life model developed in this study can be possible to configure suitable packaging conditions depending on a specific market necessity along the logistic and retail chain.

Keywords: pineapple, modified atmosphere packaging, quality properties, modeling, shelf life

Contents

Nomenclature

Symbol	Term	Unity
α	Fraction of respiratory heat absorbed	
σ	Parameter of k for the model of firmness	
μ	Parameter of k for the model of firmness	
ω	Parameter of k for the model of firmness	
a	Apparent order of reaction	
a_{wat}	Water activity in the surrounding atmosphere	
a_{wp}	Water activity in the product	
a*	CIELAB red(+)/green(−) color coordinate	
a_0*	CIELAB red(+)/green(−) color coordinate on day zero	
a_{max}*	Maximum CIELAB red(+)/green(−) color coordinate	
b*	CIELAB yellow(+)/blue(−) color coordinate	
b_0*	CIELAB yellow(+)/blue(−) color coordinate on day zero	
CK	Chemical kinetics	
E_a	Energy of activation of the Arrhenius equation	kJ mol^{-1}
EMAP	Equilibrium modified atmosphere packaging	
F	Firmness	N
F_0	Firmness on day zero of storage	N
F_{sen}	Senescence core firmness	N

Symbol	**Term**	**Unity**
q	Effective respiration heat used for the moisture transfer	kJ kg^{-1} d^{-1}
K_m	Michaelis-Menten model parameter	
k	Mass transfer coefficient (Chapter 2)	kg kg^{-1} h^{-1}
k	Firmness, L*, a* or b* parameter of change in the models proposed	
k_{0min}	Parameter of k for the model of firmness	
k_{O2}, k_{CO2}	Rate coefficients	cm^3 kg^{-1} d^{-1}
L*	CIELAB lightness coordinate	
L_0*	CIELAB lightness coordinate on day zero of storage	
L_{Fix}*	Minimum CIELAB lightness coordinate	
LDPE	Low-density polyethylene	
MAP	Modified atmosphere packaging	
MM	Michaelis-Menten simple kinetics	
n	Firmness model parameter	
P	firmness or color parameter depending on temperature	
P_{ref}	firmness or color parameter at T_{ref}	
PET	Polyethylene terephthalate	
PLA	Polylactic acid	
R	universal gas constant (0.008314)	kJ mol-1 K-1
R^2_{adj}	Adjusted coefficient of determination	
RH	Relative humidity	
r_{H2O}	Transpiration rate	kg kg^{-1} h^{-1}
r_{O2}, r_{CO2}	O_2 consumption and CO_2 production rates	cm^3 kg^{-1} h^{-1}

Symbol	**Term**	**Unity**
r_{O2}^{max}, r_{CO2}^{max}	Maximum O_2 consumption and CO_2 production rates	$cm^3\ kg^{-1}\ h^{-1}$
t	Storage time	d
$t_{shelf\text{-}life}$	Shelf life time	d
V	Free package volumen - headspace	cm^3
W	Fruit weight	kg
WL	Weight los	
y_{O2}, y_{CO2}	O_2 and CO_2 concentrations inside the package	
λ	Latent heat of water evaporation	$kJ\ kg^{-1}$

Introduction

Nowadays, consumers want to obtain products that have great nutritional and sensory characteristics, fruits and vegetables are a group of foods that have a number of characteristics desired to improve health (Bajpai, Yoon, & Chul Kang, 2009). In response to the latest trends, fresh and minimally processed products have taken relevant importance in the world market due the possibility of obtaining natural products, without additives and with high nutritional quality (Montero-Calderón, Rojas-Graü, & Martín-Belloso, 2008).

The pineapple (*Ananas comosus*) is one of the most appreciated tropical fruits in the world for its flavor, aroma, juiciness and texture, and for its excellent nutritional content (Kabir, Howlader, Ghosh, Goswami, & Haque, 2010). This produce, internationally, is mostly presented to the consumer minimally processed (cut in different shapes generally) due the difficulty to remove the crown and peel. However, with this processing the shelf life of the produce is reduced to a few days and it must be additionally processed (thermal and another intensive treatments) in the destination country, meaning an economical loss (value added) for the producer country (González-Aguilar, Ruiz-Cruz, Cruz-Valenzuela, Rodríguez-Félix, & Wang, 2004).

Colombia is recognized for being one of the ten countries that produces more pineapple worldwide, even though less than 1 % of the national production is exported and 95 % of it is fresh produce (Red de Información y Comunicación del Sector Agropecuario de Colombia - Ministerio de Agricultura y Desarrollo Rural, 2016). In this way, the development of new packaging and storage technologies to commercialize this fruit maintaining or increasing its shelf life and quality properties can be beneficial to increase economic gains for producers.

Considering the above, this thesis aims to contribute to the post-harvest and engineering areas improving the production, handling and distribution of minimally processed pineapple by developing equations that can be used to predict the shelf life at different packaging conditions.

Research aim

The aim of this thesis was to develop mathematical models, supported by experimental data, to describe changes in weight, color, firmness and shelf life of minimally processed pineapple (*Ananas comosus*) based on the influence of the packaging configuration and storage conditions. This thesis is divided in three chapters in addition to the introduction and general conclusions. The chapter one is the theoretical framework of the thesis and, the chapters two and three were written in the form of scientific articles and submitted with appropriate modifications to different research journals according to each topic.

To achieve the research aim, the following specific objectives were set:

- Determine the rates of O_2 consumption and CO_2 and water vapor generation for the minimally processed pineapple as a function of gas concentration, relative humidity and temperature, and resolve the mass balance for the modified atmospheres packaging system.

- Evaluate experimentally the effect of gas concentration, relative humidity and storage temperature on the weight, color and firmness of minimally processed pineapple packed in several modified atmospheres.

- Represent mathematically the evolution of color, firmness and weight of the minimally processed pineapple packed in modified atmospheres, depending on the packaging conditions, gas concentration, relative humidity and storage temperature.

- Determine the relationship between the shelf life of the packed product and the evolution of the weight, color, firmness and other quality properties and determine favorable conditions for its preservation.

- Validate the capacity of the model developed to predict the shelf life of minimally processed pineapple under different packaging and storage conditions.

1. Theoretical framework

1.1 Postharvest products

Post-harvest handling aims to preserve the quality obtained in the farm to take it to the consumer and consists in the operations of collection, cleaning, selection, processing, storage and transport (Calderon & Cerdas, 2005). The way these operations are carried out is going to be a determining factor in the shelf life of fruits and vegetables in general.

All the vegetable produces are living organisms that have biological systems that determine their living processes, even after harvest. In order that this systems can function suitably, two process are very relevant: respiration (oxygen consumption and carbon dioxide production) and ethylene production that classified the fruits in two particular groups: climacteric fruits that exhibit, during ripening, a large increase of carbon dioxide and ethylene, and non-climacteric fruits that do not exhibit changes in their CO_2 and ethylene production during the ripening process (Paltrinieri, 2014).

The water content and the loss of this during post-harvest is also determinant for ripening due it is necessary to perform all the metabolic processes in the plant cell. Fresh fruits in the postharvest time generally contain between 65 and 95% of water (w/w) (Paltrinieri, 2014).

1.2 Pineapple (*Ananas comosus*) fruits

Pineapple, *Ananas comosus* is native to Amazonia and Orinoquia regions, from there it spread throughout the Americas and after that to other continents such as Asia and Africa. Its origin is identified in the Mattogroso region located between Brazil and Uruguay. It belongs to the genus of Ananas, of the family of bromeliads. This fruit is a monocotyledonous, herbaceous and perennial plant that is multiplied through slips and stem cuttings, and that can reach a meter in height (Corporación Colombia Internacional, 2000).

The pineapple is a typical tropical plant that grows and develops optimally when grown between 500 and 1,300 m.a.s.l., with temperatures between 20 and 27 °C, high luminosity and water requirements of 1,000 mm per year. Climatic conditions depend on the yield of the crop, the development of the plant, the duration of the productive cycle, floral induction, the number of leaves and shoots, the collation of peel and pulp, and the organoleptic quality of the fruit (Corporación Colombia Internacional, 2000).

The pineapple is a non-climacteric fruit and considered one of the most desirable tropical fruits in the world (Kabir et al., 2010). It is appreciated worldwide for its flavor, aroma, juiciness and texture (Paull & Chen, 2003). It is a fruit with high nutritional content, high source of vitamin A, B and C, and some minerals such as calcium, phosphorus and iron (Hossain & Rahman, 2011; Kabir et al., 2010).

Marketable pineapples to export are usually packed in cardboard boxes with enough ventilation of 5 to 10 units. For cold storage the fruits can be refrigerated at temperatures between 2-12 °C, and 90% relative humidity depending on the variety of the pineapple, its ripening stage and transport conditions (Sociedad Alemana de Cooperación Técnica, 1994).

1.3 Effect of post-harvest climate conditions on the fruit quality properties

Post-harvest shelf life is the time that a fruit can be stored without becoming inadequate for its consumption. This period of availability depends on the degradation mechanisms of the product, its packaging and storage conditions (Soliva-Fortuny & Martín-Belloso, 2003).

For fresh produce, it is of great interest to evaluate the shelf life from its conditions of storage, respiration, transpiration and ethylene production to find the adequate conditions for the product to be better preserved over time.

Temperature is the most important environmental factor to take into account during post-harvest because low temperatures decrease most metabolic processes, including respiration, and likewise increases shelf life (Kader, 2002; Wills, McGlasson, Graham, & Joyce, 2007). There are some crops such as pineapple, banana and avocado in which exposure to temperatures below a limit creates stress phenomena that result in chilling injury of the fruits. Exposure to undesired temperatures could result physiological disorders that affect the microbiological, nutritional and sensory quality of the product (Kubo, 2015).

Respiration is the most important metabolic process for fresh produce during post-harvest because it is responsible for generating energy and the necessary substances to maintain cellular organization (Lee. L., Arul. J., 1996). The composition of gases surrounding the produce determines the respiration rate and therefore the process of deterioration (Kubo, 2015). Oxygen is essential in respiration and numerous metabolic reactions in plants; a decrease in the concentration of oxygen results in a decrease in the ripening rate during post-harvest, however its absence can also cause damage due to the generation of anaerobic processes that may be unwanted (Sandhya, 2010). Carbon dioxide is produced during the respiration process, however, high levels of CO_2 in the atmosphere surrounding the produce can result in decreasing the ripening and respiration rates (Watada, Ko, & Minott, 1996).

Transpiration is the process by which the fruit loss water. This loss is associated with the conditions of relative humidity in the surrounding atmosphere and the metabolic process of respiration. The decrease of water in the product is one of the biggest factors that limits the commercialization during post-harvest because it causes undesirable changes in appearance, texture, weight and taste (Lee. L., Arul. J., 1996).

Ethylene in plants regulates many important aspects such as their growth and development, as well as responses to the environment, stress and pathogen attacks. In the postharvest of fruits, ethylene control has become one of the critical points due to the physiological and metabolic responses that are generated as a consequence of both endogenous and exogenous ethylene for these products (Gapper, McQuinn, & Giovannoni, 2013).

Considering the above, it is necessary to consider conditions such as temperature, relative humidity and gas concentration in the atmosphere surrounding the fresh produce to keep shelf life, quality properties and reduce losses (García Tain, Pérez Padrón, García Pereira, & Hernández Gómez, 2011).

Desirable quality properties for fresh produce during post-harvest are: uniform shape and size, fresh appearance, firm texture, without deformations and characteristic color and aroma. They should also be products free of rottenness, sunburn, insect damage, microorganisms, bruises, wounds and cracks, clean, without inadequate odors or flavors and free of external moisture (Calderon & Cerdas, 2005).

Commercially in the packaging of fresh produce these attributes are evaluated through the senses (touch, smell and sight) by the operators that perform the selection, classification and packaging processes. In most cases, some random samples are chosen to evaluate their internal properties, such as the content of soluble solids, acidity and texture of the fruit pulp and peel (Calderon & Cerdas, 2005).

The changes in the quality of the pineapple during post-harvest, ripening and senescence lead to the different processes that make the edible product with the characteristic organoleptic properties (García Taín, García Pereira, Hernández Gómez, & Pérez Padrón, 2011). The most used quality properties for the determination of ripeness and shelf life of pineapple are pulp color, firmness and water loss because they are non-destructive and easy to measure (Chakraborty, Rao, & Mishra, 2015; García Taín et al., 2011; Liu, Hsu, & Hsu, 2007; Mandal, Lalremruata, Hazarika, & Nautiyal, 2015; Montero-Calderón et al., 2008; Ulloa, Sáenz, & Castro, 2015).

1.4 Minimally processed fresh produce

Consumers want to obtain products that have suitable nutritional and sensory characteristics, which is why it is necessary to preserve longer all of these characteristics (Fischer, 2005). Fruits and vegetables are a group of foods that have a number of characteristics desired to improve health (Bajpai et al., 2009). In response to the latest trends, fresh and minimally processed products have taken on great importance in the world market due the possibility of obtaining natural products, without additives and with high nutritional quality (Montero-Calderón et al., 2008).

Minimally processed fruits, vegetables or tubers are products the consumer can eat without additional processes while retaining almost all of these original characteristics. Generally this type of products are packaged in plastic films or containers and at low refrigeration temperatures to keep shelf lives of 7 up to 20 days depending on the product, the handling process and the storage conditions (Watada & Qi, 1999).

When the peel of the fruits is removed, their shelf life is reduced (Del Nobile, Licciardello, Scrocco, Muratore, & Zappa, 2007) because the internal tissues are exposed and become vulnerable to discoloration, dehydration, browning by enzymatic oxidation and deterioration processes that affect overall quality in attributes such as appearance, texture, weight and nutritional content (Watada & Qi, 1999). Therefore, it is necessary to study the proper packaging and storage conditions for different fruit species when this type of process is carried out.

In the literature there are studies in which has been evaluated how the different packaging and storage conditions have an effect over shelf life of minimally processed products (Ahvenainen, 1996; Rolle & Chism, 1987; Watada et al., 1996). Minimally processed pineapple with no peel is very convenient because the fruit has an inedible peel that is difficult to remove when eating. From decade of the 90s has been made some studies to evaluate conditions to increase shelf life of cut and minimally processed pineapple (Alem et al., 1994; Alemán et al., 1998; Spanier et al., 1998).

Minimally processing the pineapple (removing peel, sectioning in slices and so) generates wounds in the fruit that increases the metabolic processes, enzyme activity and substrates degradation. These processes generate an increase in respiration rate and ethylene production, reducing the product's shelf life from 1-2 weeks down to only 1-3 days, even under optimal temperature conditions (González-Aguilar et al., 2004). Additionally, this treatment increases the microbial decay generated by the contamination of the pulp with environment microorganisms, where they have availability of nutrients for their growth (González-Aguilar et al., 2004).

For this type of products different storage conditions have been evaluated determining suitable temperatures (Antoniolli, Benedetti, Sigrist, Souza Filho, & Alves, 2006; Marrero & Kader, 2006), treatments to avoid browning (González-Aguilar et al., 2004; Liu et al., 2007; Rocculi, Cocci, Romani, Sacchetti, & Rosa, 2009), packaging systems (Liu et al., 2007; Marrero & Kader, 2006; Montero-Calderón et al., 2008) and cutting configuration (Antoniolli et al., 2006).

1.4.1 Packaging

The main function of food packaging is to protect products from external influences, to contain food and to provide consumers with nutritional information (Kirwan, Plant, & Strawbridge, 2011). Likewise, food packaging must maintain safety, be convenient and minimize environmental damage (Marsh & Bugusu, 2007).

Plastics are widely used in food industry and their application has been increasing because in addition to fulfill basic functions such as containment, protection, they facilitate the consumer's consumption of the product in the modern world (Selke & Culter, 2016).

In the packaging of fruits, vegetables and tubers whole and minimally processed, it is necessary the packaging material to be permeable enough to allow the interaction and balance of the gases of the surrounding atmosphere with those generated in the packaging headspace and in this way to achieve an balance between product's respiration and transpiration and permeation through the package (Mangaraj, Goswami, & Mahajan, 2009). For this reason, to preserve fresh produce such as fruits the packaging material to be selected should have enough permeation capacity to achieve a balance between gas transfer and product metabolism at the defined storage conditions (temperature, gas concentration and relative humidity) (Exama, Arul, Lencki, Lee, & Toupin, 1993).

Materials most used to pack minimally processed products are polymers derived from petrochemical processes such as low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), terephthalate of polyethylene (PET) and polystyrene (PS) (Mangaraj et al., 2009). However, other types of polymers that have similar properties and are produced from renewable sources are currently being considered. Polylactic acid (PLA) is the most promising renewable source polymer that has been developed so far, because it can meet the characteristics necessary to pack minimally processed products besides that it is biodegradable (Raquez, Habibi, Murariu, & Dubois, 2013).

The study of the influence of packaging material for minimally processed pineapple has not been studied in depth. Polymeric materials that are generally used to pack this product are polypropylene (PP), polyethylene (PE) and polystyrene (PS) in containers and rigid clamshells (Budu & Joyce, 2005; Liu et al., 2007; Marrero & Kader, 2006; Montero-Calderón et al., 2008).

1.4.2 Modified atmosphere packaging (MAP)

Modified atmospheres are used to increase the shelf life and maintain the quality (Castellanos & Herrera, 2017; Castellanos, Polanía, & Herrera, 2016) of minimally processed food products ready to be consumed (J. H. Lee, An, Song, Jung, & Lee, 2016), these have low concentrations of oxygen (O_2) and high of carbon dioxide (CO_2) in order to slow down the process of respiration of the fruit and reduce its metabolic activity. The above is possible by altering the internal concentration of gases (oxygen, carbon dioxide, water vapor and nitrogen) in the packaging to reduce the respiration rate and decrease metabolic activity. The modified atmosphere in a packaged fresh product is generated and maintained by the dynamic interaction between the gas transfer of the package (between inside and outside the system) and the respiration and transpiration produced by the fruit, so the composition of the gases and the relative humidity in the external part of the package are also important for achieve the desired balance (Mangaraj et al., 2009; Sousa-Gallagher & Mahajan, 2013). Experimentally, it has been found that by reducing the concentration of oxygen to 8% and raising the concentration of carbon dioxide above 5 % it is possible to delay fruit ripening, however it has been found that by reducing the O_2 concentration down to 2% development of unpleasant flavors and undesired odors could be generated (Sandhya, 2010). MAP should be coupled with refrigeration and even active packaging techniques to maximize the preservation effect and increase the product's (Sandhya, 2010).

Modified atmospheres in the packaging of minimally processed fruits such as pineapple can be very convenient due the potential of this product and considering it is a method that can delay the fruit deterioration and increase its shelf life. Modified atmospheres have been used on minimally processed pineapple by some researchers with the aim of evaluating the effect of this methodology on the quality and shelf life of the fruit.

Budu et al. evaluated the effect of modified atmospheres in the minimally processed pineapple quality and found that concentrations of 2% O_2 and 10% CO_2 stabilized the respiration rate of the fruit during 14 storage days (Budu & Joyce, 2005).

Marrero et al. studied the effect of temperature and modified atmospheres in minimally processed pineapple and its shelf life, finding that by reducing the O_2 concentration down to 8% and by increasing the CO_2 concentration up to 10% at 5 °C, it is possible to keep the fruit during 2 weeks avoiding deterioration (Marrero & Kader, 2006).

Liu et al. investigated the combined effect of pretreatment with ascorbic acid and sucrose, and the use of modified atmospheres in minimally processed pineapple, finding that the shelf life of the pineapple was increased from 3 up to 7 days at 4 °C (Liu et al., 2007).

1.5 Mathematical modeling to represent the shelf life of minimally processed produces from quality properties and storage conditions

The main objective of mathematical models is to predict the future behavior of any product under a defined situation (Tijskens & Schouten, 2009). Mathematical models can be used to efficiently estimate changes in the quality of fruits affected by different conditions in the storage time. These can be useful to accurately represent a condition of the product without having to check it in real time and without affecting this. However, to develop a suitable and useful model it is necessary to perform an experimental validation to verify that that the capacity of the model is sufficient to represent the actual behavior (Tijskens & Schouten, 2009).

A number of models have been used successfully to find the combination of suitable storage conditions, gas concentration and favorable packaging systems to increase the shelf life of different fresh fruits (Castellanos, Herrera, & Herrera, 2016; Sousa-Gallagher & Mahajan, 2013).

Many models have been developed to predict respiration, color, firmness, among other properties for tomato, mango, mushrooms, lychee and pomegranate (Caleb, Mahajan, Opara, & Witthuhn, 2012; Jha, Chopra, & Kingsly, 2007; Lukasse & Polderdijk, 2003; Mangaraj & Goswami, 2008; Schouten, Huijben, Tijskens, & van Kooten, 2007).

To develop suitable mathematical models for minimally processed pineapple in modified atmospheres can be of great interest because they could predict and find the most adequate packaging and storage conditions to increase their shelf life. In Colombia this is of great interest because currently most of pineapple destined for export is sold whole and it is minimally processed in the destination countries decreasing profit margins.

In the literature, works regarding modeling with minimally processed pineapple in modified atmospheres seen to be limited finding only a couple of references. Benítez et al. studied and modeled the effect of temperature on respiration and texture of freshly cut pineapple packed in modified atmospheres for 10 days. The authors determined a model with which the benefits of different types of packaging can be estimated and can generate temperature evolution curves based on the packaging for minimally processed pineapple (Benítez, Chiumenti, Sepulcre, Achaerandio, & Pujolá, 2012). Finnegan et al. modeled fresh pineapple respiration and predicted the necessary permeability of a package with modified atmospheres. A model was obtained to predict the respiration rate of the product over time. Additionally the model can be very useful for predicting the gas composition inside he packaging system (Finnegan, Mahajan, O'Connell, Francis, & O'Beirne, 2013).

The available literature presents some advances in the modeling of characteristics of minimally processed pineapple considering the storage and packaging conditions, however, there is no available literature regarding the modeling of changes in quality properties and shelf life as far as it has been found.

1.6 Colombian case

In the case of Colombia, the production and export of fresh fruits has increased in recent years, which demonstrates the global trend that exists in this type of products and the great possibility that the country has in this market (Red de Información y Comunicación del Sector Agropecuario de Colombia - Ministerio de Agricultura y Desarrollo Rural, 2016).

Pineapple is a product of great interest in Colombia due to the increase that has occurred in terms of production and exports in recent years (Red de Información y Comunicación del Sector Agropecuario de Colombia - Ministerio de Agricultura y Desarrollo Rural, 2016). Pineapple exports have been increasing in recent years with a considerable growth of 68% between 2015 (4,882 tons) and 2016 (15,182 tons); this with 95% fresh product without any processing. In 2016, markets were opened in Chile, Portugal, Russia, France, Turkey, Saudi Arabia, Arab Emirates and Egypt. It is important to highlight that the record number of exports in 2016 does not represent even 1% of the national production of the year 2014 (652,769 tons) (Red de Información y Comunicación del Sector Agropecuario de Colombia - Ministerio de Agricultura y Desarrollo Rural, 2016). The above shows that in Colombia there are problems and limitations to market this type of products abroad and it presents an interesting opportunity to evaluate better conservation systems that allow producers and distributors to improve their export possibilities.

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2. Modeling respiration and transpiration rate of minimally processed pineapple (*Ananas comosus*) depending on temperature, gas concentrations and geometric configuration[1]

Abstract

This study presents a mathematical model to describe respiration (O_2 consumption and CO_2 production) and transpiration rates of minimally processed pineapple (cut into slices) as a function of temperature, relative humidity (RH) and geometric configuration. To experimentally adjust suitable models for respiration and transpiration, minimally processed pineapple (*Ananas comosus*) was stored in slices of three types of configuration (a complete slice with 1 centimeter of thickness, a complete slice with 2 centimeter of thickness and a half slice with 1 centimeter of thickness) at different temperature and RH. To estimate respiration rates, two possible models were compared and the most suitable one was chosen: the O_2 consumption and CO_2 production were modeled by using a Michaelis-Menten enzyme kinetics and by using a first-order kinetics selecting the former. Throughout the different experiments, the respiration rates were higher by increasing the storage temperature. The transpiration data shows the weight loss is linear for all the samples during the entire storage time. Transpiration was represented by considering the mass transfer (of moisture) due the water activity gradient between the produce and the

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[1] This chapter with minor modifications was published as:

Gómez, J.M., Castellanos, D.A., Herrera, A.O. (2019). Modeling respiration and transpiration rate of minimally processed pineapple (*Ananas comosus*) depending on temperature, gas concentrations and geometric configuration. *Chemical Engineering Transactions*, 75, 547–552. DOI: 10.3303/CET1975092.

atmosphere surrounding it, and the water evaporated because of absorbing the respiratory heat generated in the cut fruits. Results shows a high goodness of fit between experimental data and estimated values with the respiration-transpiration models (R^2>0.89).

Keywords: minimally processed pineapple, geometric configuration, respiration, transpiration, temperature

2.1 Introduction

Minimally processed products represent an important challenge to the postharvest sector because of the difficulty to preserve their nutritional and sensory quality during the commercialization. It is important to know the respiration and transpiration rates to determine the favorable gas (O_2 and CO_2) levels and relative humidity for a suitable modified atmosphere packaging (MAP). The above considering that inappropriate control of the packaging conditions may lead to undesirable results such as microbial growth, moisture condensation, accelerated physiological decay and shortened shelf life (Song et al, 2002). Respecting high perishable produce such as pineapple (moreover minimally processed), it is very desirable to establish constant and acceptable gas-temperature conditions to preserve its special nutritional and sensory qualities and to avoid rapid decay and deterioration. A number of mathematical models have been proposed to describe a MAP system and to establish favorable gas levels (Benítez et al., 2012; Finnegan et al., 2013). However, as far as it is known, scarce information is available to describe MAP (and specifically respiration-transpiration rates) for minimally processed fruits and for pineapple particularly. By knowing the respiration and transpiration rates depending on storage and packaging conditions, it could be possible to improve the postharvest handling and reduce losses for this fruit that has been one of the most consumed tropical fruits in the world.

Therefore, the aim of this study was to propose mathematical models to represent O_2 consumption, CO_2 production and transpiration (water vapor generation) rates of sliced pineapple depending on temperature, gas concentration and cutting configuration.

2.2 Materials and methods

2.2.1 Fruits

Pineapples (*Ananas comosus*) MD2 were provided by a local fruit store in Bogotá, Colombia the evening before each trial and stored at 12 °C up to 16 hours until minimal processing. Samples without evidence of damage were selected, cleaned with potable water and left to dry (surface water) at room temperature before the processing stage.

2.2.2 Fruit processing

The pineapple crown and peels were removed manually by using a clean stainless-steel knife. Three types of configuration were cut: a complete slice of one-centimeter thickness and 10-centimeter diameter approximately, a complete slice of two-centimeter thickness and a half of a slice of one-centimeter thickness.

2.2.3 Determination of the respiration rates

The respiration rates (O_2 consumption and CO_2 generation) of the minimally processed pineapple were determined by using a closed system method (Mendoza, Castellanos, García, Vargas, & Herrera, 2016). Two samples of each pineapple slices configurations, previously described, were placed in a hermetic container of 2176 cm^3 separated by a grid of 5- centimeter height. The O_2 and CO_2 concentrations were determined with an electronic analyzer Oxybaby® 6i (WITT-Gasetechnik GmbH & Co KG, D-58454 Witten, Germany). The tests were performed in cabinets with controlled temperature at 8, 12.5, 17 and 21 $\pm$ 0.5°C and taking measurements every 2.5 hours until reaching an O_2 concentration of 5%. All the measurements for each configuration were performed in triplicate and reporting the average value of each measurement.

The respiration rates were calculated at each temperature by using the following equations:

$$r_{O_2}(t) = \left(\frac{V}{W}\right)\left(\frac{y_{O_2 t-1} - y_{O_2 t+1}}{\Delta t}\right) \tag{2.1}$$

$$r_{CO_2}(t) = \left(\frac{V}{W}\right)\left(\frac{y_{CO_2 t+1} - y_{CO_2 t-1}}{\Delta t}\right) \tag{2.2}$$

Where $r_{O_2}(t)$ and $r_{CO_2}(t)$ are the respirations rates at time t (cm^3 kg^{-1} h^{-1}), V is the free package volume (cm^3), W is the slice weight (kg) and Δt is the time pass between two consecutive measurements (h). y_{O_2t-1}, y_{CO_2t-1} are the O_2 and CO_2 mole fractions in the preceding measurement than the time t and y_{O_2t+1}, y_{CO_2t+1} are the following measurement than the time t.

2.2.4 Determination of the transpiration rates

The transpiration rates were estimated measuring the experimental weight loss of the minimally processed pineapple configuration slices, described above, using open trays. The change in the sample weight was measured using an Ohaus analytical balance PA-3102 (OHAUS Corp. Pine Brook, NJ, USA). The samples were stored in a Sanyo-Panasonic MLR-352H-PE cabinet (SANYO Electric Co., Osaka, Japan) with controlled temperature and relative humidity, at 8, 12.5 and 17 $\pm$ 0.3°C, and at 60, 70, 80 and 90 $\pm$ 0.1% RH. The weight measurement was performed every 3 hours for 36 hours. All the samples configurations were performed in triplicate and presenting the average of each measurement.

Transpiration rate was calculated at each temperature using the following equations:

$$r_{H_2O}(t) = \frac{W_{t-1} - W_{t+1}}{W_t \Delta t} \qquad (2.3)$$

Where $r_{H_2O}(t)$ is the transpiration rate at time t (kg kg^{-1} h^{-1}), Δt is the time pass between two consecutive measurements (h) and W_t is the slice weight (kg). W_{t-1} the weight in the preceding measurement than the time t and W_{t+1} is the following measurement (kg) than the time t.

2.2.5 Modeling the respiration rates

The respiration of the fruits has been described using mathematical equations to model biochemical systems because of their appropriate representation of the nature of the process and good fit of experimental data. Between these equations are relevant the Michaelis-Menten equations based on the enzyme kinetics principle and the Chemical Kinetics equations based on the apparent reaction order.

The Michaelis-Menten Kinetics (MM) equation is based on one limiting enzymatic reaction in which the substrate is O_2. The respiration rate, r_{O_2} and r_{CO_2}, is (Fonseca et al, 2002; Heydari et al, 2010):

$$r_{O_2} = \frac{r_{O_2}^{max} y_{O_2}}{K_{m_{O2}} + y_{O_2}} \tag{2.4}$$

$$r_{CO_2} = \frac{r_{CO_2}^{max} y_{O_2}}{K_{m_{CO2}} + y_{O_2}} \tag{2.5}$$

Likewise, the Chemical Kinetics (CK) equation is considered to explain the effect of O_2 and CO_2 concentrations on the respiration rates (Wang et al, 2009):

$$r_{O_2} = k_{O_2} y_{O_2}^{a_{O2}} \tag{2.6}$$

Similar equations for MM and CK could be described for the CO_2 production rate, also as a function of y_{O_2}.

To determine the respiration rate models (O_2 consumption and CO_2 production) of minimally processed pineapple, the Michaelis-Menten enzyme kinetics (MM) and the chemical kinetics (CK) equations were used. The experimental data of r_{O_2}, r_{CO_2}, y_{O_2} and y_{CO_2} at each temperature were replaced in the linearized form of the MM and CK equations to obtain the model parameters by multiple linear regressions. The models regressions were compared by the coefficient of determination R^2 adjusted (Spiess et al, 2010) that allows the comparison between non-linear models.

The temperature-influence was estimated by adjusting the parameters of each equation in the linearized form of the Arrhenius equation obtaining the pre-exponential factors and the activation energies for each parameter (Castellanos et al, 2017).

2.2.6 Modeling the transpiration rates

Considering that the transpiration process could be described as the water loss in the product because of evaporation (heat transfer) and because of the concentration differences between the product and the surrounding atmosphere (mass transfer) (Castellanos et al, 2016b), the following equation can be written:

$$r_{H_2O} = \frac{q}{\lambda} + k(a_{wp} - a_{wat}) \quad (2.7)$$

Where r_{H_2O} is the transpiration rate (kg kg^{-1} h^{-1}), q is the respiratory heat (kJ kg^{-1} h^{-1}), λ is the latent heat of moisture evaporation (kJ kg^{-1}), k is the total mass transfer coefficient (kg kg^{-1} h^{-1}), a_{wp} is the water activity in the product and a_{wat} is the water activity in the surrounding atmosphere (RH/100).

2.2.7 Model assumptions and numerical solution

For the development and use of the models the next assumptions were made:

- The product is in thermal equilibrium with the atmosphere surrounding.
- The temperature dependent processes can be modelled using the Arrhenius' law.
- The respiration and transpiration processes of the product are not affected by the ripening.
- Inside the package there is no stratification of the gases.
- The system pressure corresponded to the atmospheric pressure.
- The product not regain the water lost.

2.3 Results and discussion

2.3.1 Respiration rates

Figure 2.1 presents the respiration rate (O_2 consumption, r_{O_2}) of the minimally processed samples and for the three types of geometrical configurations, as a function of O_2 inside the hermetic containers (values estimated using Eq. 2.1 and Eq. 2.2). As the figure shows, the O_2 consumption rate decrease at lower levels of O_2 in the container headspace. The respiration rate measured for the one-centimeter half configuration was higher than the other two configurations (1x1 cm and 1x2 cm) at the same temperature. Possibly, the above is due the additional cut made in the pineapple sample that can induce increasing in respiration as a consequence of the additional injury (Artés-Hernández et al, 2007). Additionally, the one-centimeter slice has a higher O_2 consumption rate than the two-centimeter slice at the same temperature, in this case due the higher surface area/weight ratio in the former.

Likewise, the respiratory behavior of the minimally processed samples was described by using the MM and CK equations showing the adjusted values for the O_2 production and CO_2 consumption rates in Figure 2.1. These values were calculated using the Eq. 2.4 and Eq. 2.5.

The temperature-dependence of the MM parameters (r_{max} and K_m) and of the CK parameters (k) was estimated by using the Arrhenius equation. The respective parameters (pre-exponential factors and activation energies) were determined by linear regression and are shown in Table 2.1. The positive values in the activation energies for all the parameters shows a direct relationship among temperature and respiration rates. The apparent reaction order (*a*) in the CK equation probed to be temperature-independent.

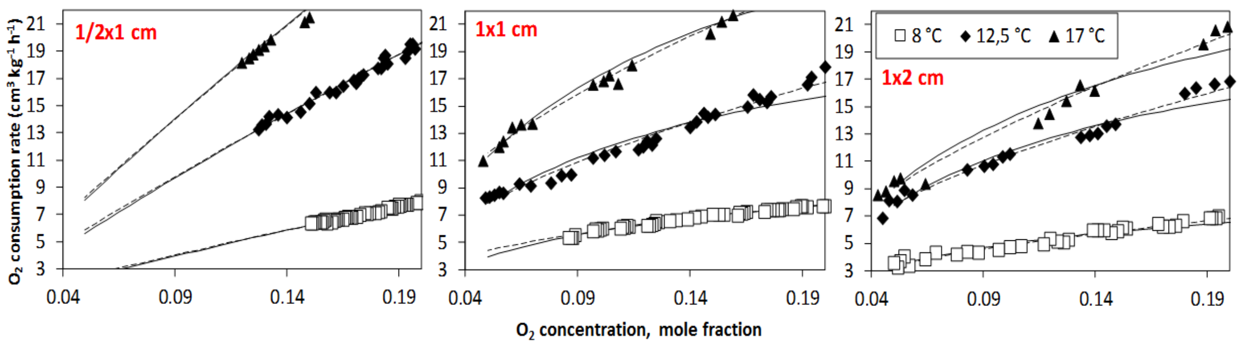

Figure 2.1. O_2 consumption rate of the three slice-configuration (1/2x1 cm, 1x1 cm and 1x2 cm) as a function of O_2 concentration at 8 °C, 12.5 °C and 17 °C. Symbols represent experimental data and lines represent the predicted values using the Michaelis-Menten (---) and Chemical Kinetics (- - -) equations.

By comparing the coefficients of determination R^2 for each of the respiration models it was found that both (MM and CK) adequately represent the respiratory behavior of the minimally processed pineapple for the different evaluated temperatures. Other studies have demonstrated that the respiration of fresh-cut fruits correspond to an enzymatic process (Lee et al, 1996; Peppelenbos et al, 1996), for this reason the Michaelis-Menten enzyme equation is more appropriate to represent this process. This affirmation is confirmed by the work carried out by Benitez et al (Benítez et al., 2012).

Table 2.1. Estimated parameters for O_2 consumption and CO_2 production rates of the one-centimeter slice, two- centimeter slice and one-centimeter half slice for Michaelis-Menten enzyme (MM) and for Chemical Kinetic equations.

Model	½ x1 cm slice		1x1 cm slice		1x2 cm slice	
	O_2	**CO_2**	**O_2**	**CO_2**	**O_2**	**CO_2**
Michaelis-Menten Eq.						
r_{max} (cm^3 kg^{-1} h^{-1})						
$r_{max\text{-}ref}$ (cm^3 kg^{-1} h^{-1})	1.09±0.03x10^{22}	1.91±0.10x10^{23}	3.27±0.07x10^{17}	9.17±0.34x10^{19}	1.45±0.02x10^{17}	6.12±0.37x10^{25}
E_a (kJ mol^{-1})	109.94 ± 2.75	119.46 ± 6.33	88.67 ± 1.77	103.50 ± 3.83	86.96 ± 1.48	135.39 ± 8.12
K_m						
$K_{m\text{-}ref}$	640.80 ± 16.02	1.34±0.07x10^{10}	33.02 ± 0.66	1.76 ± 0.65	43.57 ± 0.74	7.31±0.44x10^{10}
E_a (kJ mol^{-1})	15.33 ± 0.38	59.24 ± 3.14	13.73 ± 0.27	9.07 ± 0.34	14.35 ± 0.24	65.92 ± 3.95
R^2_{adj}	0.973	0.883	0.948	0.970	0.903	0.938
Chemical Kinetics Eq.						
a	0.87 ± 0.02	0.57 ± 0.03	0.50 ± 0.01	0.27 ± 0.01	0.54 ± 0.01	0.41 ± 0.02
k (cm^3 kg^{-1} h^{-1})						
k_{ref} (cm^3 kg^{-1} h^{-1})	9.90±0.25x10^{20}	6.10±0.32x10^{21}	1.48±0.03x10^{20}	8.87±0.33x10^{21}	1.72±0.03x10^{18}	4.21±0.25x10^{27}
E_a (kJ mol^{-1})	104.79 ± 2.62	110.35 ± 5.85	101.98 ± 2.04	113.45 ± 4.20	91.58 ± 1.56	144.37 ± 8.66
R^2_{adj}	0.965	0.996	0.947	0.998	0.932	0.921

Rmax: maximum respiration rate (O_2 consumption or CO_2 production); rmax-ref: maximum rate, pre-exponential factor; Km: Michaelis-Menten constant; Km-ref: Michaelis-Menten constant, pre-exponential factor; a: apparent reaction order; k: rate coefficient; kref: rate coefficient, pre-exponential factor; Ea: apparent activation energies; R2adj: adjusted coefficient of determination.

2.3.2 Transpiration rates

The transpiration rates of the minimally processed pineapple for the different configurations were calculated from the cumulative weight loss data (Eq. 2.3). As shown in Figure 2.2, the samples weight loss increases linearly during the storage time. The fruit weight loss was greater by increasing the storage temperature, being the highest at 17 °C. After 30 hours of storage, the weight loss of the samples stored at 17 °C was 2 times higher than that of the product stored at 8 °C at the lowest relative humidity. In addition, the weight loss for the cut fruits was greater as the relative humidity of the atmosphere surrounding the slices was lower. This because a greater difference in water activity between the samples and the atmosphere results in a high driving force for water evaporation (Becker et al, 2001).

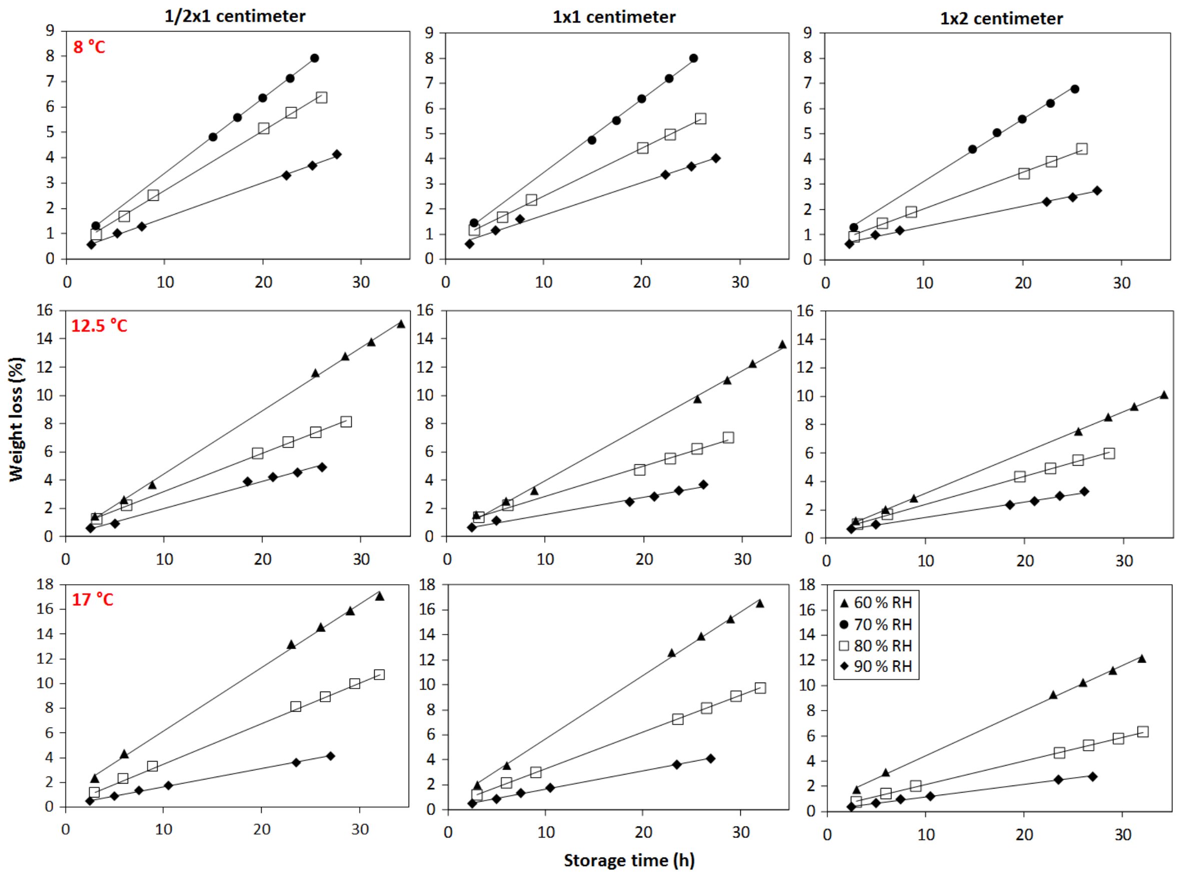

Figure 2.2. Cumulative weight loss for the pineapple slices stored in open trays at 8 °C, 12.5 °C and 17 °C. The symbols represent experimental data and the lines represent weight loss predicted by model.

With the experimental the transpiration rates estimated at every temperature and slice-configuration and by using Eq. 2.6, it was possible to obtain coefficients of mass transfer (k) and the fraction of respiratory heat absorbed to evaporate water (α) in the cut fruits for each combination temperature and slice-configuration. Then, with the mass transfer coefficients calculated at each temperature, the temperature-dependence was determined by using the Arrhenius equation estimating the parameters performing a linear regression for every slice configuration. In addition, the fraction of respiratory heat turned out to be independent of the temperature.

The overall transpiration model has a high goodness of fit respecting the experimental values measured with R^2 higher than 0.95. These data are shown in Table 2.2.

Table 2.2. Parameters for the calculation of the transpiration rate based on the respiratory heat and the water activity difference.

Configuration	½ x1 cm slice	1x1 cm slice	1x2 cm slice
Respiration heat			
α	0.64 ± 0.03	0.68 ± 0.03	0.58 ± 0.03
Mass transfer due the water partial pressure difference			
k (cm^3 kg^{-1} h^{-1})			
k_{ref} (cm^3 kg^{-1} h^{-1})	116333.72 ± 4071.68	499298.50 ± 14978.96	7162.47 ± 250.69
E_a (kJ mol^{-1})	38.65 ± 0.96	42.51 ± 1.06	33.14 ± 0.83
R^2_{adj}	0.996	0.954	0.950

k_{ref}: reference mass transfer coefficient, pre-exponential factor; E_a: apparent activation energies.

The mathematical models described in this study to represent the behavior of the respiration and transpiration rates could be very useful to set specific equilibrium concentration of O_2 and CO_2, and weight loss by properly modifying the configuration package and storage conditions.

2.4 Conclusions

Experimental measurements show that higher area/weight relation, higher temperature and higher O_2 concentration leads to greater respiration and transpiration rates in the cut pineapple. In addition, was observed that extra cuts in the pineapple slices accelerated its metabolic processes.

The proposed models were adjusted satisfactorily to the data obtained experimentally and they can be used to predict respiration and transpiration of minimally processed pineapple at different storage temperatures.

For the continuation of the experiments, the complete slice of 1 cm thickness was selected because this slice presents respiration and transpiration speeds similar to the complete slice of 2 cm at the lowest temperature evaluated. In addition, for a direct consumer product this slice is thinner and therefore easier to consume.

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3. Modeling shelf life of minimally processed pineapple (*Ananas comosus*) in modified atmosphere packaging from quality-indicative properties and storage conditions[2]

3.1 Abstract

Cut pineapple slices of 1cm thick were packaged at different temperatures and gas concentrations to determine changes of firmness, color and other physicochemical properties over time with the aim to represent shelf life depending on temperature and gas concentration from the evolution of these quality properties. From the experimental data, models were adjusted to represent the change of each one of these properties as a function of temperature and O_2 concentration by using a power model for firmness and first-order models to represent color. From the statistical analysis of the experimental data was deduced that the color (CIELAB) coordinates evolution is independent on gas concentration. From the model of firmness was possible to obtain a suitable equation to predict shelf life of the pineapple slices for different equilibrium modified atmosphere packaging (EMAP), obtaining R^2_{adj}>0.90. Finally, a validation experiment was performed with EMAP at 8 °C obtaining a high capacity of prediction.

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[2] This chapter with minor modifications was submitted for publication as:

Gómez, J.M., Mendoza, S.M., Herrera, A.O., Castellanos, D.A. (2019). Modeling shelf life of minimally processed pineapple (*Ananas comosus*) in modified atmosphere packaging from quality-indicative properties and storage conditions. *Food Packaging and Shelf Life*. In peer review.

Keywords: pineapple, modified atmosphere packaging, quality properties, modeling, shelf life

3.2 Introduction

The minimally processed products represent an important opportunity in the current market because consumers want to obtain products that are easy to consume with high nutritional and sensorial quality (Fischer, 2005). However, these products regularly have a short shelf life due to the fact that their internal tissues are exposed and become vulnerable to external factors that affect negatively their quality attributes (Del Nobile et al., 2007).

Minimally processing of pineapple (removing peel, sectioning in slices and so) generates wounds in the fruit that increases the metabolic processes, enzyme activity and substrates degradation. These cutting processes reduce the product’s shelf life from 1-2 weeks down to only 1-3 days, even under optimal temperature conditions (González-Aguilar et al., 2004). Additionally, this processing increases the microbial decay generated by the contamination of the pulp with environmental microorganisms, where they have availability of nutrients for their growth (González-Aguilar et al., 2004).

Modified atmosphere packaging (MAP) and storage conditions, nowadays, have been used to increase the shelf life of highly perishable products due that it is useful to slowing down the metabolic processes that affect the ripening and deterioration on the produce (Hertog, Nicholson, & Jeffery, 2004).

In order to describe the shelf life as a function of the MAP and storage conditions, it is possible to find a relationship between the behavior of some quality-properties such as firmness and color and the senescence stage of the stored produce (Maria Luisa Amodio, Derossi, & Colelli, 2013). Likewise, it is possible to find a relationship between changes in quality properties and shelf life of the fresh produce and the temperature and gas concentration in the packaging system over time. So, the shelf life could be represented by the change of the quality properties over the time taking into account that there will be values of senescence for each one of the quality-properties (Maria L. Amodio, Derossi, & Colelli, 2017; Hertog, Nicholson, et al., 2004; Nannyonga, Bakalis, Andrews, Mugampoza, & Gkatzionis, 2016).

Considering the above the aim of this study was to estimate shelf life of minimally processed pineapple in cut slices and stored in equilibrium modified atmosphere packaging (EMAP) by taking into account changes in color and texture and their relationship with packaging conditions such as temperature and gas concentration.

3.3 Materials and methods

3.3.1 Fruits

Pineapples (*Ananas comosus*) MD2 were provided by a local fruit store in Bogotá, Colombia the evening before each trial and stored at 12 °C up to 16 hours until minimal processing. Fruits used for all the experiments were selected based on the external appearance with a ripening stage 2 of 4 according with the pineapple color stage guide (De La Cruz Medina & García, 2005). Pineapples without evidence of damage were selected for the subsequent trials.

3.3.2 Fruit handling

The pineapples samples were first cleaned with abundant fresh water to eliminate dust and dirt and after that were immersed in a 200-ppm sodium hypochlorite solution for 2 minutes and washed at room temperature. Second, the crown was carefully removed manually in each fruit avoiding tissue damage. After that, the samples without crown were immersed again in 200 ppm sodium hypochlorite solution for 2 minutes at room temperature, washed again with fresh water and left to dry (surface water) at room temperature (approx. 17 °C) before the processing stage.

In the processing stage, the pineapple peels were removed manually by using a clean stainless-steel knife. The samples were cut in slices of one-centimeter thickness and 10-centimeter diameter approximately. The core of the slices was not removed. All the knives, tables and surfaces were previously sanitized.

3.3.3 Packages

The pineapple slices were packaged on polyethylene terephthalate (PET) rigid clamshells of 710 cm^3 sealed with a film on the top with a gas exchange area of 130 cm^2. To seal the clamshells were used low-density polyethylene (LDPE) films with low permeability to water vapor and polylactic acid (PLA) films with high permeability to water vapor. The LDPE films (Proveplas S.A.S, Bogotá, Colombia) had a thickness of 0.05 ± 0.005 mm and PLA films (ClearBags, El Dorado Hills, CA, USA) had a thickness of 0.03048 ± 0.005 mm and 0.0381 ± 0.005 mm.

3.3.4 Finding a relationship between quality properties and shelf life and packaging configuration

This study was conducted starting from the premise that it is possible to represent the shelf life of the cut pineapple samples from the evolution in their indicative quality properties such as firmness and color (Castellanos, Polanía, et al., 2016) and that the changes in these properties are a function of packaging and storage conditions such as temperature and level of gases in the packages (Sierra, Londoño, Gómez, Herrera, & Castellanos, 2019). According to this, different EMAPs were pre-configured at different constant temperatures taking into account that the fruit respiration and transpiration (Gomez, Castellanos, & Herrera, 2019) were in equilibrium with the gas transfer in the packaging system. Thus, different combinations of constant levels of gases and temperature were obtained. Cut samples were stored in each of these combinations, evaluating the evolution of their quality properties and deterioration. Finally, the relationship between these changes and the packaging conditions was estimated in order to obtain a suitable equation to represent shelf life. This was validated with an additional experiment.

3.3.5 EMAP configuration at different temperatures

To determine the influence of gas concentration and temperature on the evolution of the quality properties and the cut pineapple shelf life, different packaging configurations were pre-established, varying the packaging permeation capacity to obtain different constant concentrations of gases at each storage temperature according to the respiration and transpiration of the samples. This to represent the relationship between fruit shelf life and gas concentrations and temperature. The equilibrium configurations were pre-established according to what was proposed by Castellanos et al. (2016a) by using the differential mass balances for each gas and considering the gas transfer through the package walls and perforations, and the O_2 consumption and CO_2 and water vapor generation from the packed fruit.

In order to obtain the different EMAP combinations, the pineapple slices were packed into the sealed rigid PET clamshells as described above with the PLA and LDPE films to reach a balance between product respiration-transpiration and gas transfer through the packaging system.

The respiration and transpiration rates of the cut pineapples were estimated in a previous study (Gomez et al., 2019) as explained in Chapter 2. The respiration of the cut pineapples was represented by enzymatic kinetics of Michaelis-Menten as a function of O_2 and CO_2 concentrations and temperature. Likewise, the transpiration of the samples was described by using a function that takes into account the water evaporation due to the difference in water activities between the cut fruit and the atmosphere surrounding it and the heat of respiration (Gomez et al., 2019).

The mass transfer of the gases in the MAP system was represented by considering the gas permeation through the packaging film and diffusion through the perforations made in it. In some combinations, perforations were necessary in the first place to increase the packaging transfer capacity to avoid oxygen depletion and possibility of fermentation and in the second place to vary to a greater extent the concentrations of constant gases reached in each EMAP at each temperature evaluated.

The permeability coefficients of the LDPE and PLA packages to O_2 and CO_2 were taken from the manufacturers' data sheets (Proveplas S.A.S and ClearBags) and from data found in scientific articles (Almenar & Auras, 2010; Hasbullah, Gardjito, A.M., & Akinaga, 2000; Techavises & Hikida, 2008).

The gas transmission through the perforation was estimated according with the study of Castellanos et al. (2016a) by considering that the transfer through the perforations can be described using a modified Fick's equation of diffusion.

In order to obtain the equilibrium concentrations of each gas inside the EMAP (O_2, CO_2, water vapor), the mass balance equations were solved numerically at each storage temperature taking into account the fruit respiration and transpiration rates and the permeation rates through the film and the perforations (Castellanos, Herrera, et al., 2016).

3.3.6 Making the EMAP combinations and storage

To determine the relationship between evolution of quality properties and shelf life, and packaging conditions, samples of pineapple cuttings were packed at three temperatures (5.5, 12.5 and 17 ° C) with four packing configurations for each temperature (i.e. four concentrations of gases) as shown in Table 3.1.

Table 3.1. Experimental design and equilibrium concentration of O_2 (yO_2) and CO_2 (yCO_2) in each packaging system (LDPE is low density polyethylene and PLA is Polylactic acid).

Temperature (°C)	Packaging (thickness in µm)	Number of perforations (diameter in µm)	Eq. yO_2	Eq. yCO_2
5.5	LDPE (50.0)	0	0.023	0.034
5.5	PLA (38.1)	1 x 132	0.146	0.044
5.5	PLA (38.1)	2 x 132	0.166	0.032
5.5	LDPE (50.0)	2 x 365	0.195	0.011
12.5	LDPE (50.0)	0	0.012	0.054
12.5	PLA (38.1)	1 x 132	0.095	0.101
12.5	PLA (38.1)	2 x 132	0.124	0.077
12.5	PLA (30.5)	3 x 365	0.186	0.022
17	LDPE (50.0)	0	0.012	0.093
17	PLA (30.5)	1 x 132	0.072	0.136
17	PLA (38.1)	1 x 365	0.147	0.066
17	PLA (30.5)	3 x 365	0.173	0.038

One slice of pineapple with a total weight of 119.98 ± 15.36 grams were placed in each PET clamshell and manually sealed with the LDPE or PLA film according to the case (Table 3.1). Each of the packages had an effective transfer area of 130 ± 3.52 cm^2 (through the film specifically) and a headspace volume of 560.32 ± 15.32 cm^3. The packed slices were stored at the different temperatures with 60 ± 2 % relative humidity (RH) between 4 to 14 days depending on deterioration evidence and evolution of the quality properties. According to the combination the films were perforated to reach the wanted concentrations of O_2 and CO_2 inside the packages obtaining two possible perforation diameters: 132 ± 54 µm or 365 ± 54 µm (Table 3.1). The perforation diameter was verified with an Olympus® CX31 optical microscope (Olympus Co., Tokyo, Japan).

The change of the O_2 and CO_2 concentrations in each package was measured with an electronic analyzer Oxybaby® 6i (WITT-Gasetechnik GmbH & Co KG, D-58454 Witten, Germany). The change in RH was measured by using a digital humidity/temperature meter

CC-4096 Traceable® (Control Company, Friendswood, TX, USA) that was adhered to one of the internal package walls to prevent it from touching the cut pineapple sample.

To determine the evolution in quality and shelf life of the cut samples, an acceptability index, weight loss, firmness, color, sugar and acid content were measured on even days until the sample was discarded. For each measurement day, three EMAP replicates were used reporting the mean value of each evaluated property.

3.3.7 Fruit quality properties

First, the acceptability of the pineapple slices were evaluated visually based on a scale previously applied with some modifications (González-Aguilar et al., 2004). A 9 to 1 scale was used, where 9 = excellent (no defects), 7 = very good (minor defects), 5 = fair (moderate defects), 3 = poor (major defects or presence of fermented smell and/or visual presence of fungus) and 1 = unusable (advanced deterioration and presence of fermented smell and/or visual presence of fungus). The condition 5 was considered the limit of marketability.

The change in the pineapple slice weight was measured by using an Ohaus analytical balance PA-3102 (OHAUS Corp. Pine Brook, NJ, USA), with an accuracy of ± 0.01 grams. The weight loss was calculated using the next equation:

$$\mathrm{WL(t)\%} = \frac{(W_{ini} - W_t) * 100}{W_{ini}} \tag{3.2}$$

Where W_{ini} is the initial weight and W_t is the fruit weight at day t.

The color of the pineapple slices was measured in the center of the core. The measurement was made by using a Minolta ChromaMeter (Model CR-331, Minolta Camera Co., Osaka, Japan), and reporting the CIELAB color coordinates L*, a* and b*. 'Daylight 65' was considered as the standard illuminant. All the measurements for each configuration were performed in triplicate and reporting the average value of each measurement.

The firmness was measured in the center of the core of each pineapple slice (subjected to transversal puncture) using a Universal Testing Machine with a 3 mm Magness-Taylor probe at a preload force of 1 N and a test speed of 2 mm s^{-1}. The firmness was taken as the maximum force (N) needed to penetrate the fruit to a depth of 5mm. All the measurements for each configuration were performed in triplicate and reporting the average value of each measurement.

To analyze the content of organic acids and sugars, 5 ± 0.2 g of the pineapple slices were blended with 40 cm^3 of a sulfuric acid solution (0.04 mM) for the organic acids and with 40 cm^3 of type I water for the sugar quantification. Then the mixtures were put in Falcon® tubes and centrifugated at 3100 rpm for 44 minutes. The supernatants were stored at -18°C and then filtered using a 0.22 µm membrane filter before being analyzed. The analyzes were performed using a Thermo Dionex Ultimate 3000 uHPLC with the Chromeleon® 7.2 software, a LPG-3400SD pump, a UV-Vis detector DAD 3000 and an IR detector RefractoMax 521 (Waltham, MA, USA). To perform the analysis a Nova-Pack C-18 column (150 x 4.6 mm and 4 µm particle size) was used (Waters Corp., Milford, USA).

For organic acids the optimum efficiency of separation (isocratic system) was obtained by using a sulfuric acid solution (0.04 mM) (Solvent A) with blends of methanol (Solvent B) in a 99.2:0.8 % ratio, respectively. Operating conditions were injection volume of 0.01 cm^3, column temperature of 35 °C and a flow rate of 1.0 cm^3 min^{-1}. The citric and malic acids were quantified by using the UV-Vis detector at 210 nm and the oxalic acid was quantified using an IR detector (Gündüz & Özdemir, 2014; Shui & Leong, 2002).

For sugars the optimum efficiency of separation (isocratic system) for the saccharose, glucose and fructose were obtained by using a sulfuric acid solution (4mM) (solvent A) and acetonitrile (Solvent B) in a 75:25 % ratio. Operating conditions were injection volume of 0.01 cm^3, column temperature of 35 °C and a flow rate of 1.0 cm^3 min^{-1}. The saccharose, glucose and fructose content were quantified using the IR detector. All the measurements were done in triplicate reporting the mean value of each one in mg g^{-1} of fruit.

The effect of the different packaging conditions in the cut fruit properties was determined with an analysis of variance and the significant differences between them was established by using a Tukey's HSD test ($p < 0.05$) for each one of the response variables. Statistical analyzes were performed using the R-3.2 software (The R Foundation, Indianapolis, IN, USA).

Based on this statistical analysis it was possible to analyze the influence of the storage temperature and the equilibrium gas concentrations over the quality properties of the minimally processed pineapple and in consequence to establish their relationship by using convenient mathematical equations.

3.3.8 Modeling color and firmness

Having the experimental data from the color and firmness of the fruits stored at each packaging system and storage temperature, appropriate equations were proposed to represent the experimental data by considering the shape of the curves of data. The model adjustment was done by proposing equations that could be fitted to the experimental data as a function of the time at the different packaging conditions evaluated. Likewise, the statistical analysis performed before was considered to determine if the effect of each factor (temperature, O_2 or CO_2 concentration) was significant in the changes of fruit color and firmness. The influence of the O_2 concentration and temperature over the samples and their properties were determined by fitting the data to the proposed equations and by estimating the corresponding parameters (Castellanos & Herrera, 2017).

3.3.9 Modeling shelf life

After suitable equations were found to fit the experimental evolution of firmness and color as a function of temperature and O_2 concentration in the different EMAPs, the most suitable quality-property model was taken to represent shelf life. The model was chosen by considering the effect of temperature and O_2 concentration could be clearly observed for the different EMAP combinations used. To obtain the shelf life model, in the equation corresponding to the change of the chosen property over time the value of this was replaced by the one corresponding to the senescence stage and then the time was isolated from the equation. This time is the one corresponding to the product shelf life, now the dependent variable. The senescence stage was that was corresponding when the pineapple slices reach condition 3 or less (see above in fruit quality properties).

3.3.10 Validation test

After obtaining the equations and parameters to estimate firmness, color and shelf life of the pineapple slices in the EMAP systems, a validation test was conducted to determine the capacity of each equation to represent new experimental data. The packaging systems for this validation test are shown in Table 3.2. Packed slices were stored at 8 °C and 60 % RH for period of 10 days. The changes in fruit weight, O_2 and CO_2 concentrations, color coordinates, firmness and acceptability index were measured. The results of this experiment were compared with the ones predicted by the models and the adjusted coefficients of determination R^2 were calculated for the simulated values respecting the experimental data (Spiess & Neumeyer, 2010).

Table 3.2. Packaging systems configuration for the validation test of the pineapple slices.

Storage temperature (°C)	Material (thickness in μm)	Number of perforations	Diameter of perforation (μm)
8	LDPE (50.0)	0	-
8	PLA (38.1)	1	132
8	PLA (30.5)	2	365

3.4 Results and discussion

Table 3.3 presents the properties of the pineapple slices at the beginning of the storage. These values were later used as initial values in the color, firmness and shelf life models and were additionally used for comparison purposes.

Table 3.3. Physico-chemical properties of the pineapple slices.

Parameter	Ripening stage 2 of 4** (day zero)
Weight per slice (g)	119.98 ± 15.36
Color parameters (CIELAB)	
L*	70.16 ± 0.53
a*	-3.74 ± 0.20
b*	31.50 ± 0.15
Firmness (N)	19.87 ± 0.03
Citric acid (*g kg*$^{-1}$)	815.91 ± 40.80
Sugar (g kg^{-1}*)*	
Sucrose	10682.52 ± 534.13
Glucose	8965.36 ± 448.27
Fructose	2326.68 ± 116.33

**Pineapple color stage guide (De La Cruz Medina & García, 2005).

3.4.1 EMAP configurations

With all the combinations of packaging and temperature (Table 3.1) was possible to reach equilibrated O_2 and CO_2 levels. The Figure 3.1 present the experimental data of the change of O_2 and CO_2 concentrations of each EMAP configuration over time (symbols) and the estimation performed with the mass balance equations for the MAP system. As can be seen in the plots, the experimental concentration of gases for each one of the configurations were close enough to the data estimated with the MAP model. In all the EMAP systems

100 % RH was reached in the packaging headspace. Some water condensation was observed in the internal surface of the packages being more abundant in the packages with LDPE due the lower permeability to water vapor.

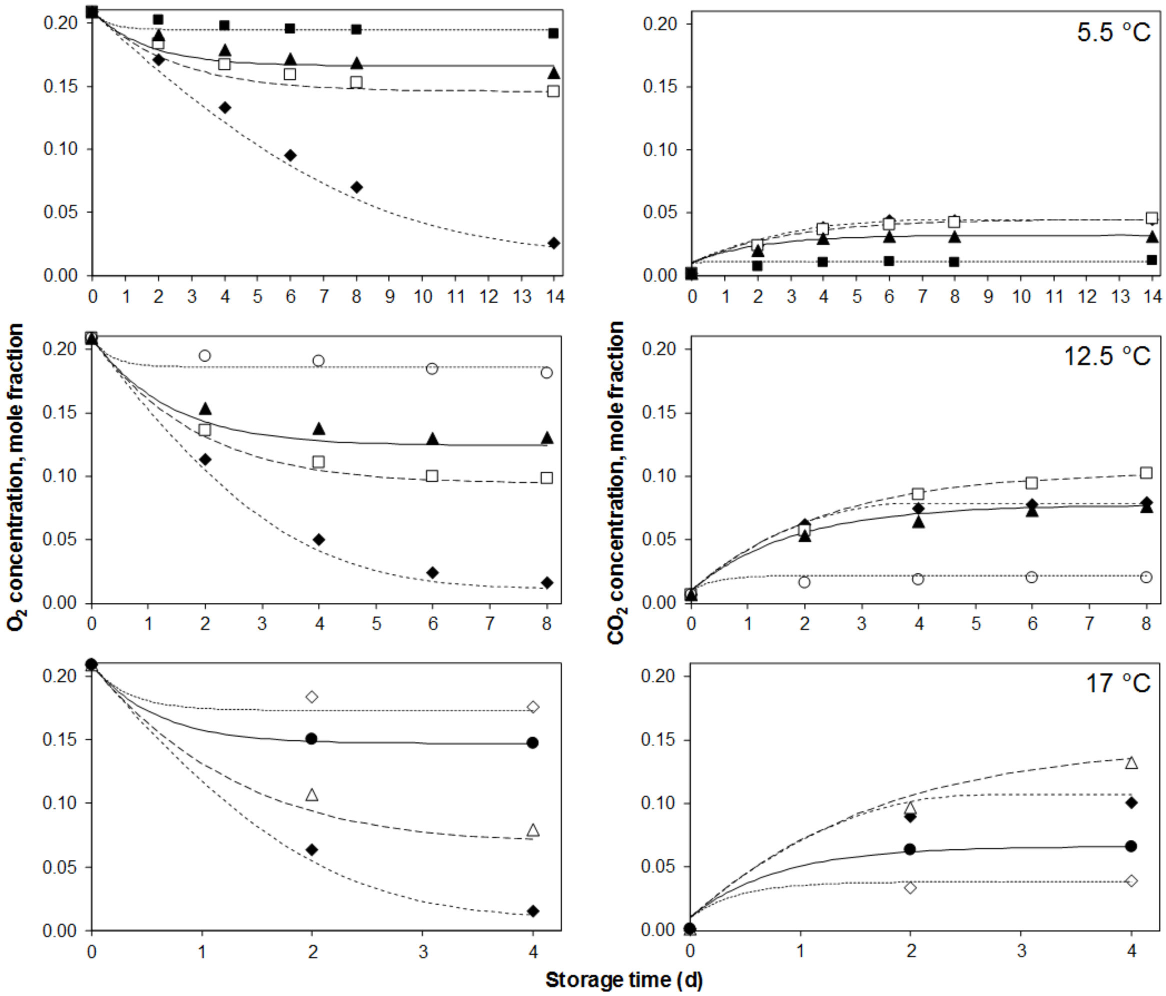

Figure 3.1. Experimental (symbols) and predicted (lines) O_2 and CO_2 change inside each one of the packaging configurations. Predicted O_2 and CO_2 concentrations using the modified atmosphere package (MAP) model proposed by Castellanos et al. (2016a).

3.4.2 Acceptability index

Table 3.4 presents the acceptability index of the minimally processed pineapple at each one of the configuration systems proposed. The slices stored at 5.5 °C were the ones that had the lower deterioration rate during the storage time compared to the samples at 12.5 and 17 °C. Additionally, at 5.5 °C the samples packed using the PLA films (38.10 µm) with two 132 µm perforations had a lower acceptability index in the day 14 than the samples with LDPE and PLA (38.10 µm) without perforations, with one 132 µm perforation and with two 365 µm perforations, that presented a similar deterioration rate. At 12.5 °C the samples packed using the LDPE without perforations had more deterioration evidence in day 8 than the samples packed using PLA of 30.50 and 38.10 µm with one and two 132 µm perforations, and three 365 µm perforations. At 17 °C, the acceptability index was similar for the 4 combinations at day 4 of storage.

Table 3.4. Acceptability index of the pineapple slices during the storage time in the EMAP systems.

Parameter	EMAP	Day 0	Day 2	Day 4	Day 6	Day 8	Day 14
Acceptability Index*	5.5/LDPE/no	9	9	9	9	5	3
	5.5/PLA 38.1/1x132	9	9	9	9	7	3
	5.5/PLA 38.1/2x132	9	9	9	9	7	5
	5.5/LDPE/2x365	9	9	9	7	7	3
	12.5/LDPE/no	9	9	7	5	3	. .
	12.5/PLA 38.1/1x132	9	9	7	5	3	. .
	12.5/PLA 38.1/2x132	9	9	7	5	5	. .
	12.5/PLA 30.5/3x365	9	9	7	5	3	. .
	17/LDPE/no	9	5	3	. .	. .	. .
	17.0/PLA 30.5/1x132	9	7	3	. .	. .	. .
	17.0/PLA 38.1/1x365	9	7	3	. .	. .	. .
	17.0/PLA 30.5/3x365	9	7	3	. .	. .	. .

*9 = excellent, 7 = very good, 5 = fair, 3 = poor and 1 = unusable

3.4.3 Weight loss

Cumulative weight loss of the minimally processed pineapple at each one of the configuration systems is shown in Table 3.5. The weight loss of the samples packed using the LPDE films with or without perforations were lower than the samples packed using the PLA films with or without perforations. Respecting the storage temperature, the weight loss was greater at higher temperature as shown in Table 3.5. At 17 °C, the weight loss was 1.79 % at day 4 using the PLA (30.50 µm) package with three 365 µm perforations while at 12.5 °C and 5.5 °C with LDPE without perforations the corresponding weight loss were 0.51 % at day 8 and 0.37 % at day 14 respectively. As probed with the experimental data, the slices using the PLA films have a higher transpiration because this material has a higher permeability to the water vapor than the LDPE. Additionally, the packages with more perforations made the samples transpiration higher because it takes more time to the package to get the headspace saturation (more transfer area).

Table 3.5. Weight loss of the pineapple slices during the storage time in the equilibrium modified atmosphere packages (EMAP) systems.

Parameter	EMAP	Day 0	Day 2	Day 4	Day 6	Day 8	Day 14
Weight loss (%)	5.5/LDPE/no	0.00±0.00^{a}	0.05±0.01^{a}	0.09±0.01^{abc}	0.12±0.02^{abc}	0.16±0.02^{abcd}	0.37±0.07^{bcdefgh}
	5.5/PLA 38.1/1x132	‘’	0.21±0.05^{abcde}	0.41±0.09^{cdefghi}	0.60±0.12^{ghij}	0.80±0.19^{jkl}	1.53±0.33^{nop}
	5.5/PLA 38.1/2x132	‘’	0.18±0.01^{abcd}	0.39±0.02^{cdefgh}	0.65±0.10^{hijk}	0.80±0.08^{jkl}	1.41±0.11^{no}
	5.5/LDPE/2x365	‘’	0.02±0.01^{a}	0.04±0.01^{a}	0.05±0.02^{a}	0.07±0.02^{ab}	0.22±0.07^{abcde}
	12.5/LDPE/no	‘’	0.06±0.03^{ab}	0.10±0.05^{abc}	0.26±0.03^{abcdef}	0.51±0.03^{efghij}	. .
	12.5/PLA 38.1/1x132	‘’	0.21±0.04^{abcde}	0.46±0.12^{defghi}	0.80±0.12^{jkl}	1.24±0.13^{mn}	. .
	12.5/PLA 38.1/2x132	‘’	0.26±0.08^{abcdef}	0.54±0.09^{fghij}	0.95±0.20^{klm}	1.53±0.20^{nop}	. .
	12.5/PLA 30.5/3x365	‘’	0.31±0.07^{abcdefg}	0.60±0.09^{ghij}	1.00±0.08^{lm}	1.48±0.17^{nop}	. .
	17/LDPE/no	‘’	0.05±0.02^{a}	0.14±0.04^{abcd}	. .	. .	. .
	17.0/PLA 30.5/1x132	‘’	0.72±0.09^{ijkl}	1.71±0.20^{op}	. .	. .	. .
	17.0/PLA 38.1/1x365	‘’	0.63±0.07^{hij}	1.50±0.11^{nop}	. .	. .	. .
	17.0/PLA 30.5/3x365	‘’	0.82±0.04^{jkl}	1.79±0.10^{p}	. .	. .	. .

Means with different letters across each column and row are significantly different at $P \leq 0.05$ by the Tukey’s HSD test. Standard deviation (SD) included.

3.4.4 Color

Table 3.6 and Table 3.7 present the core color of the minimally processed pineapple at each one of the configuration systems evaluated. In all the cases, the lightness L* and the b* coordinate decreased, and the a* coordinate values increased.

It is important to clarify that the color and firmness change during the storage time was measured in the core due the fruit anatomy and ripeness pattern in the flesh has a high variability.

The color coordinates of the slice core significantly changed from the initial day at the same temperature and packaging configuration. When comparing the values at the same day at different storage temperatures, it can be observed that the values are significantly different. But when comparing the behavior of the color coordinates between the different packaging configurations (different O_2 concentrations) at same temperature can be seen that there is no significant difference between them. This was concluded after performing the statistical Tukey´s test.

Table 3.6. Core lightness (L* coordinate) of the pineapple slices during the storage time in the equilibrium modified atmosphere packages (EMAP) systems.

Parameter	EMAP	Day 0	Day 2	Day 4	Day 6	Day 8	Day 14
	5.5/LDPE/no	70.16±0.53^{a}	69.23±0.29^{abc}	68.62±0.26^{abcdef}	68.34±0.46^{bcdef}	68.18±0.10^{bcdefg}	66.32±0.21^{ijklmn}
	5.5/PLA 38.1/1x132	“	68.63±0.53^{abcdef}	67.59±0.35^{cdefghij}	67.06±0.48^{efghijkl}	66.61±0.32^{ghijklm}	65.17±0.60^{mnop}
	5.5/PLA 38.1/2x132	“	69.63±0.2^{ab}	69.16±0.21^{abc}	68.76±0.46^{abcde}	68.46±0.41^{bcdef}	67.60±0.10^{cdefghij}
	5.5/LDPE/2x365	“	69.28±0.29^{abc}	68.57±0.07^{bcdef}	68.04±0.15^{bcdefgh}	67.67±0.12^{cdefghij}	66.59±0.6^{ghijklm}
	12.5/LDPE/no	“	69.02±0.92^{abcd}	67.79±0.22^{cdefghij}	67.10±1.04^{efghijkl}	66.55±0.89^{ghijklm}	. .
	12.5/PLA 38.1/1x132	“	67.86±0.38^{cdefghij}	66.35±0.15^{hijklm}	64.61±0.17^{nop}	64.20±0.05^{p}	. .
L*	12.5/PLA 38.1/2x132	“	68.22±0.08^{bcdefg}	66.44±0.06^{hijklm}	65.38±0.29^{lmnop}	64.49±0.25^{op}	. .
	12.5/PLA 30.5/3x365	“	68.73±0.96^{abcde}	67.25±0.77^{efghijk}	66.16±0.36^{jklmno}	65.02±0.43^{mnop}	. .
	17/LDPE/no	“	67.43±0.46^{defghijk}	65.76±0.13^{klmnop}	. .	. .	. .
	17.0/PLA 30.5/1x132	“	68.34±0.15^{bcdef}	66.60±0.10^{ghijklm}	. .	. .	. .
	17.0/PLA 38.1/1x365	“	68.51±0.70^{bcdef}	66.99±0.11^{fghijkl}	. .	. .	. .
	17.0/PLA 30.5/3x365	“	68.04±0.12^{bcdefghi}	67.04±0.09^{efghijkl}	. .	. .	. .

Means with different letters across each column and row are significantly different at P ≤ 0.01 by the Tukey’s HSD test. Standard deviation (SD) included.

In accordance with other studies, the color of the pineapple slices during the storage became darker and less yellow compared with the samples on day zero (Budu & Joyce, 2005; González-Aguilar et al., 2004; Rocculi et al., 2009). This means that the values of L* and b* decreased along the storage time as can be observed from the experimental data (Table 3.6 and Table 3.7). This behavior is explained by the phenolic oxidation that is made by the polyphenol oxidase enzymes that form colored melanins (Budu & Joyce, 2003).

Table 3.7. Red (+) / green (-) core color (a* coordinate) and Yellow (+) / Blue (-) core color (b* coordinate) of the pineapple slices during the storage time in the equilibrium modified atmosphere packages (EMAP) systems (LDPE is low density polyethylene and PLA is Polylactic acid).

Parameter	EMAP	Day 0	Day 2	Day 4	Day 6	Day 8	Day 14
a*	5.5/LDPE/no	-3.74 ± 0.20^{a}	-3.37 ± 0.11^{ab}	-3.17 ± 0.06^{abcdef}	-3.14 ± 0.09^{abcdefg}	-3.02 ± 0.12^{abcdefgh}	$-2.51\pm0.09^{defghijklm}$
	5.5/PLA 38.1/1x132	“	-3.33 ± 0.28^{abc}	-3.05 ± 0.36^{abcdefgh}	-2.90 ± 0.23^{bcdefghij}	-2.78 ± 0.10^{bcdefghij}	$-2.52\pm0.16^{cdefghijklm}$
	5.5/PLA 38.1/2x132	“	-3.26 ± 0.10^{abcd}	-2.95 ± 0.08^{abcdefghi}	-2.81 ± 0.08^{bcdefghij}	$-2.74\pm0.13^{bcdefghijk}$	-2.33 ± 0.26^{ghijklmn}
	5.5/LDPE/2x365	“	-3.30 ± 0.18^{abcd}	-3.05 ± 0.32^{abcdefgh}	-3.00 ± 0.49^{abcdefgh}	-2.89 ± 0.26^{bcdefghij}	$-2.37\pm0.13^{efghijklmn}$
	12.5/LDPE/no	“	-3.39 ± 0.12^{ab}	-2.94 ± 0.21^{abcdefghi}	$-2.75\pm0.06^{bcdefghijk}$	$-2.69\pm0.12^{bcdefghijkl}$	· ·
	12.5/PLA 38.1/1x132	“	$-2.65\pm0.09^{bcdefghijklm}$	-2.18 ± 0.45^{ijklmno}	-1.67 ± 0.05^{no}	-1.67 ± 0.05^{o}	· ·
	12.5/PLA 38.1/2x132	“	-3.17 ± 0.16^{abcde}	$-2.69\pm0.08^{bcdefghijklm}$	-2.29 ± 0.07^{hijklmn}	-1.90 ± 0.06^{lmno}	· ·
	12.5/PLA 30.5/3x365	“	-3.01 ± 0.27^{abcdefgh}	-2.81 ± 0.05^{bcdefghij}	$-2.53\pm0.05^{cdefghijklm}$	-1.95 ± 0.20^{klmno}	· ·
	17/LDPE/no	“	$-2.59\pm0.22^{bcdefghijklm}$	-1.88 ± 0.56^{mno}	· ·	· ·	· ·
	17.0/PLA 30.5/1x132	“	-3.01 ± 0.38^{abcdefgh}	$-2.50\pm0.19^{defghijklm}$	· ·	· ·	· ·
	17.0/PLA 38.1/1x365	“	$-2.64\pm0.30^{bcdefghijklm}$	-2.11 ± 0.16^{jklmno}	· ·	· ·	· ·
	17.0/PLA 30.5/3x365	“	-2.36 ± 0.08^{fghijklmn}	-1.91 ± 0.23^{lmno}	· ·	· ·	· ·
b*	5.5/LDPE/no	31.50 ± 0.15^{a}	30.28 ± 0.12^{abcdefghi}	29.48 ± 0.13^{cdefghij}	29.09 ± 0.15^{fghijk}	28.82 ± 0.35^{hijk}	27.80 ± 0.22^{k}
	5.5/PLA 38.1/1x132	“	30.90 ± 0.39^{abcd}	30.50 ± 0.62^{abcdefg}	30.29 ± 0.81^{abcdefghi}	30.12 ± 0.47^{abcdefghi}	28.64 ± 0.12^{ijk}
	5.5/PLA 38.1/2x132	“	30.09 ± 0.01^{abcdefghi}	29.31 ± 0.16^{defghijk}	29.17 ± 0.36^{efghijk}	29.01 ± 0.58^{fghijk}	27.67 ± 0.22^{k}
	5.5/LDPE/2x365	“	31.11 ± 0.94^{abc}	30.57 ± 0.94^{abcdef}	$29.89\pm0.39^{abcdefghij}$	29.70 ± 0.24^{bcdefghij}	28.43 ± 0.80^{jk}
	12.5/LDPE/no	“	30.59 ± 0.20^{abcdef}	$29.98\pm0.14^{abcdefghij}$	29.19 ± 0.07^{efghijk}	28.77 ± 0.17^{hijk}	· ·
	12.5/PLA 38.1/1x132	“	31.14 ± 0.28^{ab}	30.74 ± 0.09^{abcde}	$30.04\pm0.12^{abcdefghij}$	29.58 ± 0.11^{bcdefghij}	· ·
	12.5/PLA 38.1/2x132	“	30.85 ± 0.09^{abcd}	30.25 ± 0.09^{abcdefghi}	29.60 ± 0.06^{bcdefghij}	29.17 ± 0.12^{efghijk}	· ·
	12.5/PLA 30.5/3x365	“	30.41 ± 0.54^{abcdefgh}	29.63 ± 0.51^{bcdefghij}	29.28 ± 1.97^{defghijk}	29.09 ± 0.84^{fghijk}	· ·
	17/LDPE/no	“	30.33 ± 0.12^{abcdefgh}	28.86 ± 0.16^{ghijk}	· ·	· ·	· ·
	17.0/PLA 30.5/1x132	“	30.36 ± 0.14^{abcdefgh}	29.61 ± 0.04^{bcdefghij}	· ·	· ·	· ·
	17.0/PLA 38.1/1x365	“	31.38 ± 0.06^{ab}	$29.97\pm0.14^{abcdefghij}$	· ·	· ·	· ·
	17.0/PLA 30.5/3x365	“	30.38 ± 0.19^{abcdefgh}	$29.97\pm0.17^{abcdefghij}$	· ·	· ·	· ·

Means with different letters across each column and row are significantly different at $P \leq 0.01$ by the Tukey's HSD test. Standard deviation (SD) included.

3.4.5 Firmness

The changes in the firmness of the core slices are shown in Table 3.8 at each of the EMAP systems. As mentioned before, the firmness change during the storage time was measured in the core due it was very variable when was measured in the slice flesh. The same was found by Montero-Calderón et al. (2008) who conducted a texture profile analysis (TPA) an found that there is not a uniform pattern on the behavior of the texture of the flesh of sliced pineapple. This could be explained by the complexity of the fruit anatomy (composed of up to 200 fruitlets, each on with different types of tissues) and maturity pattern that starts from the base of the fruit and moves up to the crown (Paull & Chen, 2003).

The core firmness in the samples decreased from 19.87 N down to 16.50 N on day 4 for the slices packed using the PLA film (30.50 µm + 3 perforations) at 17 °C. The latter value corresponds in this case to the lowest equilibrium firmness.

As can be observed by comparing the different packaging systems on the same measurement day, at higher temperatures the effect on the loss of firmness of the pineapple slices is significantly greater (Table 3.8). At the same temperature, the fruits packed with an equilibrium concentration of 14.5 % of O_2 on average (5.5 °C PLA of 38.10 µm with two 132 µm perf., 12.5 °C PLA of 38.10 µm with one 132 µm perf. and 17 °C with one 365 µm perf.) had a lower firmness loss compared to the other packaging configurations. The above shows that the firmness loss rate was decreasing for O_2 concentrations between 1.6 and 14.5 % and the loss rate was increasing for O_2 concentrations between 14.5 % and 18.5 %, finding that for an O_2 and CO_2 concentration approx. of 14.5 and 5.8 % the firmness loss rate was minimal at the different temperatures. Additionally, after performing the statistical Tukey´s test, it can be observed that both temperature and the O_2 concentration have a significant influence on the decreasing of the core firmness in the slices over the storage time.

Table 3.8. Core firmness of the pineapple slices during the storage time in the equilibrium modified atmosphere packages (EMAP) systems (LDPE is low density polyethylene and PLA is Polylactic acid).

Parameter	EMAP	Day 0	Day 2	Day 4	Day 6	Day 8	Day 14
Firmness	5.5/LDPE/no	19.87±0.03^{a}	19.53±0.09^{cde}	19.26±0.13^{fg}	19.07±0.12^{ghij}	18.84±0.09^{jk}	16.54±0.07^{t}
	5.5/PLA 38.1/1x132	‘’	19.79±0.03^{ab}	19.60±0.02^{bcd}	19.31±0.06^{efg}	19.12±0.07^{ghi}	17.51±0.13^{r}
	5.5/PLA 38.1/2x132	‘’	19.85±0.09^{a}	19.74±0.06^{abc}	19.53±0.05^{cde}	19.43±0.02^{def}	18.89±0.10^{ijk}
	5.5/LDPE/2x365	‘’	19.68±0.10^{abc}	19.27±0.06^{bcde}	18.88±0.11^{fg}	17.90±0.07^{hij}	17.26±0.08^{s}
	12.5/LDPE/no	‘’	19.39±0.11^{def}	19.07±0.02^{ghij}	18.52±0.08^{lm}	17.85±0.08^{pq}	. .
	12.5/PLA 38.1/1x132	‘’	19.76±0.05^{abc}	19.30±0.07^{efg}	18.70±0.13^{kl}	18.06±0.05^{op}	. .
	12.5/PLA 38.1/2x132	‘’	19.86±0.04^{a}	19.57±0.09^{bcd}	18.98±0.06^{hij}	18.40±0.07^{mn}	. .
	12.5/PLA 30.5/3x365	‘’	19.54±0.06^{bcde}	19.22±0.10^{fgh}	18.68±0.12^{kl}	18.03±0.02^{op}	. .
	17/LDPE/no	‘’	18.37±0.08^{mn}	15.96±0.09^{u}	. .	. .	. .
	17.0/PLA 30.5/1x132	‘’	18.86±0.05^{jk}	17.74±0.09^{qr}	. .	. .	. .
	17.0/PLA 38.1/1x365	‘’	19.13±0.09^{ghi}	18.19±0.04^{no}	. .	. .	. .
	17.0/PLA 30.5/3x365	‘’	18.56±0.09^{lm}	16.50±0.10^{t}	. .	. .	. .

Means with different letters across each column and row are significantly different at $P \leq 0.05$ by the Tukey’s HSD test. Standard deviation (SD) included.

The firmness behavior shown above can be explained because low O_2 concentrations seems to promote the production of anaerobic metabolites, fermentative included, that are produced from substrates (mostly sucrose) in the cell membrane (Wszelaki & Mitcham, 2000) and high CO_2 concentrations within the packages seem to promote the physiological damage resulting in loss of cellular compartmentation and water leakage (Budu & Joyce, 2005). On the other hand, high O_2 concentrations leads to higher respiration rates that degrades the cell membrane and carries up to a higher rate of firmness loss (Kader, 2002). Having explained the above it is assumed that the minimal rate of firmness loss at 16.6 % of O_2 and 2.9 % of CO_2 can be a consequence of the intermediate gas concentrations that leads to a better conservation of the slices. That is moderate O_2 and CO_2 levels inside the packaging headspace. Not so high O_2 levels and low CO_2 levels to accelerate the oxidation processes neither so high CO_2 levels and low O_2 levels as to generate processes of anaerobic degradation.

3.4.6 Citric acid content

The citric acid content for each one of the packaging configurations during the storage time is shown in Table 3.9. The concentration measured was significantly different compared to the zero-day value, except for some values of the day 2 of storage. As can be observed from the experimental data, the storage temperature has the greatest effect on the decrease of the citric acid of the pineapple slices. The gas concentration seems to have no influence on the degradation of the acid contained in the samples, only a significant difference where observed for the packaging configuration of LPDE with 2 perforations of 365 μm (19.5 % O_2 concentration) where a greater loss of acid was observed.

The above could be explained by the oxidation reaction of the citric acid that occurs when the O_2 concentration is higher in the headspace, the acid is used as substrate in the respiration process and energy during the storage (Banda, Caleb, Jacobs, & Opara, 2015; Selcuk & Erkan, 2015).

Table 3.9. Content of citric acid of the pineapple slices during the storage time in the equilibrium modified atmosphere packages (EMAP) systems (LDPE is low density polyethylene and PLA is Polylactic acid).

Parameter	EMAP	Day 0	Day 2	Day 4	Day 6	Day 8	Day 14
Citric acid (g kg^{-1})	5.5/LDPE/no	815.91±40.80^{a}	811.32±40.57^{a}	803.94±40.20^{ab}	793.75±39.69^{abc}	778.70±38.93^{abcd}	419.49±20.97^{pqrs}
	5.5/PLA 38.1/1x132	“	731.57±36.58^{abcdef}	645.17±32.26^{efghijk}	556.72±27.84^{klmn}	545.05±27.25^{klmno}	463.93±23.20^{nopq}
	5.5/PLA 38.1/2x132	“	753.81±37.69^{abcde}	697.51±34.88^{bcdefgh}	647.01±32.35^{efghijk}	582.77±29.14^{ijklm}	414.83±20.74^{pqrs}
	5.5/LDPE/2x365	“	710.57±35.53^{abcdefg}	629.66±31.48^{fghijk}	573.17±28.66^{jklmn}	536.44±26.82^{klmno}	287.64±14.38^{t}
	12.5/LDPE/no	“	746.03±37.30^{abcde}	697.18±34.86^{bcdefgh}	510.81±25.54^{lmnop}	436.52±21.83^{opqr}	· ·
	12.5/PLA 38.1/1x132	“	792.27±39.61^{abcd}	682.26±34.11^{defghij}	477.81±23.89^{mnopq}	396.50±19.83^{qrst}	· ·
	12.5/PLA 38.1/2x132	“	684.50±34.23^{cdefghi}	596.06±29.80^{hijkl}	475.45±23.77^{mnopq}	289.78±14.49^{t}	· ·
	12.5/PLA 30.5/3x365	“	773.83±38.69^{abcd}	763.33±38.17^{abcd}	583.27±29.16^{ijklm}	469.57±23.48^{nopq}	· ·
	17/LDPE/no	“	728.05±36.40^{abcdef}	340.20±17.01^{rst}	· ·	· ·	· ·
	17.0/PLA 30.5/1x132	“	613.22±30.66^{ghijkl}	413.77±20.69^{pqrs}	· ·	· ·	· ·
	17.0/PLA 38.1/1x365	“	622.66±31.13^{fghijk}	311.99±15.60st	· ·	· ·	· ·
	17.0/PLA 30.5/3x365	“	444.51±22.23^{opqr}	372.20±18.61^{qrst}	· ·	· ·	. .

Means with different letters across each column and row are significantly different at P ≤ 0.05 by the Tukey's HSD test. Standard deviation (SD) included.

3.4.7 Sugar content

The sucrose, glucose and fructose content for each one of the packaging configurations during the storage time is shown in Table 3.10. The sugars concentration measured was significantly different compared to the zero-day value, except for some values of the day 2 of storage. As can be observed, the storage temperature has the greatest effect on the decrease of the sugars. Apparently, the gas concentration has no effect over the degradation of the sugars because the experimental data don't show a consistent behavior. As explained before, the sugars degradation is explained by the metabolic processes trigger by the different EMAP configurations experienced.

Table 3.10. Sucrose, glucose and fructose content (g kg^{-1}) of the pineapple slices during the storage time in the equilibrium modified atmosphere packages (EMAP) systems (LDPE is low density polyethylene and PLA is Polylactic acid).

Parameter	EMAP (Code)	Day 0	Day 2	Day 4	Day 6	Day 8	Day 14
Sucrose (g kg^{-1})	5.5/LDPE/no	10682.52±534.13^{a}	9997.25±499.86^{abc}	9211.97±460.60^{bcde}	8326.68±416.33^{efghij}	6912.08±345.60^{klmno}	3355.69±167.78^{w}
	5.5/PLA 38.1/1x132	“	8640.46±432.02^{defghi}	7109.72±355.49^{jklmn}	6090.29±304.51^{mnopqrs}	5887.41±294.37^{nopqrst}	4894.44±244.72^{rstuv}
	5.5/PLA 38.1/2x132	“	10452.71±522.64^{ab}	9817.66±490.88^{abcd}	8777.36±438.87^{cdefgh}	7672.98±383.65^{fghijkl}	4781.33±239.07^{stuv}
	5.5/LDPE/2x365	“	8715.15±435.76^{cdefgh}	7635.66±381.78^{fghijkl}	7444.02±372.20^{hijklm}	6155.01±307.75^{mnopqr}	4629.22±231.46^{tuvw}
	12.5/LDPE/no	“	7292.38±364.62^{ijklm}	6491.07±324.55^{lmnopq}	5674.93±283.75^{opqrstuv}	5654.26±282.71^{opqrstuv}	. .
	12.5/PLA 38.1/1x132	“	9942.78±497.14^{abcd}	7959.50±397.98^{efdhijk}	6919.49±345.97^{klmno}	5157.41±257.87^{qrstuv}	. .
	12.5/PLA 38.1/2x132	“	8896.32±444.82^{cdefg}	7548.95±377.45^{ghijkl}	6572.63±328.63^{lmnop}	5548.95±277.45^{pqrstuv}	. .
	12.5/PLA 30.5/3x365	“	6443.65±322.18^{lmnopq}	6514.55±325.73^{lmnop}	5697.10±284.85^{opqrstu}	5254.26±262.71^{pqrstuv}	. .
	17/LDPE/no	“	6402.97±320.15^{lmnopq}	4882.52±244.13^{rstuv}	. .	. .	. .
	17.0/PLA 30.5/1x132	“	4528.61±226.43^{uvw}	4319.12±215.96^{vw}	. .	. .	. .
	17.0/PLA 38.1/1x365	“	6933.49±346.67^{klmno}	5761.75±288.09^{nopqrstu}	. .	. .	. .
	17.0/PLA 30.5/3x365	“	8905.97±445.30^{cdef}	5434.06±271.70^{pqrstuv}	. .	. .	. .
Glucose (g kg^{-1})	5.5/LDPE/no	8965.36±448.27^{a}	7574.95±378.75^{bcdefg}	6580.24±329.01^{ghij}	5981.23±299.06^{hijk}	5640.02±282.00^{jkl}	1551.90±77.59st
	5.5/PLA 38.1/1x132	“	7036.67±351.83^{efgh}	5646.28±282.31^{jkl}	4798.17±239.71^{lmn}	4750.64±237.53^{lmn}	1234.44±61.72^{t}
	5.5/PLA 38.1/2x132	“	6574.97±328.75^{ghij}	4737.70±236.89^{lmn}	3453.56±172.68^{opq}	3447.27±172.36^{opq}	2654.86±132.74^{qr}
	5.5/LDPE/2x365	“	8473.75±423.69^{abc}	7955.65±397.78^{abcde}	7411.04±370.55^{cdefg}	5930.60±296.53^{ijk}	3902.85±195.14^{nop}
	12.5/LDPE/no	“	8313.42±415.67^{abc}	7149.22±357.46^{defg}	5979.12±298.96^{hijk}	1718.11±85.91^{rst}	. .
	12.5/PLA 38.1/1x132	“	8594.10±429.71^{ab}	8204.52±410.23^{abcd}	1640.13±82.01^{rst}	1347.54±67.38^{t}	. .
	12.5/PLA 38.1/2x132	“	6783.28±339.16^{fghi}	4447.23±222.36^{mno}	3222.07±161.10^{pq}	3220.45±161.02^{pq}	. .
	12.5/PLA 30.5/3x365	“	7667.20±383.36^{bcdef}	7107.82±355.39^{efg}	4781.00±239.05^{lmn}	3283.60±164.18^{pq}	. .
	17/LDPE/no	“	4239.67±211.98^{mnop}	4144.95±207.25^{mnop}	. .	. .	. .
	17.0/PLA 30.5/1x132	“	4194.25±209.71^{mnop}	2535.23±126.76^{prs}	. .	. .	. .
	17.0/PLA 38.1/1x365	“	4679.12±233.96^{lmn}	1674.31±83.72^{rst}	. .	. .	. .
	17.0/PLA 30.5/3x365	“	5210.02±260.50^{klm}	1663.82±83.19^{rst}	. .	. .	. .
Fructose (g kg^{-1})	5.5/LDPE/no	2326.68±116.33^{bc}	1957.20±97.86^{defgh}	1758.51±87.93^{ghijklm}	1730.60±86.53^{ghijklm}	1536.50±76.82^{lmnopq}	1256.70±62.83^{pqrs}
	5.5/PLA 38.1/1x132	“	2209.49±110.47^{cd}	2079.97±104.00^{cdef}	1938.11±96.91^{defgh}	1448.01±72.40^{mnopq}	965.92±48.30^{stu}
	5.5/PLA 38.1/2x132	“	2198.10±109.91^{cd}	2047.72±102.39^{cdefg}	1875.51±93.78^{efghij}	1545.87±77.29^{klmnopq}	889.18±44.46^{uv}
	5.5/LDPE/2x365	“	2135.81±106.79^{cde}	1975.20±98.76^{defgh}	1844.85±92.24^{efghijkl}	1681.01±84.05^{hijklmn}	929.99±46.50^{tuv}
	12.5/LDPE/no	“	2121.40±106.07^{cde}	1943.73±97.19^{defgh}	1788.88±89.44^{fghijkl}	1234.93±61.75^{prst}	. .
	12.5/PLA 38.1/1x132	“	2139.35±106.97^{cde}	1864.73±93.24^{efghijk}	986.31±49.32^{rstu}	969.95±48.50^{stu}	. .
	12.5/PLA 38.1/2x132	“	2717.72±135.89^{a}	1938.07±96.90^{defgh}	1911.42±95.57^{defghi}	612.48±30.62^{v}	. .
	12.5/PLA 30.5/3x365	“	2311.52±115.58	1781.05±89.05^{fghijkl}	1374.70±68.73^{nopq}	1304.28±65.21^{opqr}	. .
	17/LDPE/no	“	1692.08±84.60^{hijklmn}	1359.99±68.00^{opq}	. .	. .	. .
	17.0/PLA 30.5/1x132	“	1730.65±86.53^{ghijklm}	1454.52±72.73^{mnopq}	. .	. .	. .
	17.0/PLA 38.1/1x365	“	2563.01±128.15^{ab}	1561.95±78.10^{jklmnop}	. .	. .	. .
	17.0/PLA 30.5/3x365	“	1610.57±80.53^{ijklmno}	890.72±44.54^{uv}	. .	. .	. .

Means with different letters across each column and row are significantly different at $P \leq 0.05$ by the Tukey's HSD test. Standard deviation (SD) included.

3.4.8 Most suitable EMAP system

According to the change of the deterioration rate and the evaluated quality-properties for each EMAP systems, 16.6 % of O_2 and 2.8 % of CO_2 the package using the PLA (38.10 µm) with 2 perforations of 132 µm at 5.5 °C granted the longest shelf life of 14 days for the pineapple slices.

3.4.9 Modeling color and firmness

From the experimental behavior shown in Table 3.6, Figure 3.2 (L*), Figure 3.3 (a*) and Figure 3.4 (b*), it was observed that there was no significant differences respecting the different EMAP at the same temperature. That is, the color of the core of the pineapple slices present no influence by the O_2 concentration at each one of the temperatures according with the experimental data. For this reason, in the modeling of the three color coordinates the effect of O_2 concentration was not considered due this effect is not statistically significant. The models proposed for the changes in the color coordinates over times were adjusted only as a function of storage temperature.

The decrease of lightness (L*) in the pineapple core slice was modeled as a function of the storage time using a first-order model (Eq. 3.6) and a first-order model with fractional conversion (Eq. 3.7) based on the experimental data.

$$\mathrm{L^*}\,(\mathrm{t}) = \mathrm{L}_0^*\,\mathrm{e}^{-\mathrm{kt}} \tag{3.6}$$

$$\mathrm{L^*}\,(\mathrm{t}) = \mathrm{L}_{\mathrm{Fix}}^* + (\mathrm{L}_0^* - \mathrm{L}_{\mathrm{Fix}}^*)\,\mathrm{e}^{-\mathrm{kt}} \tag{3.7}$$

In Eq. 3.6 and 3.7, L^*_0 and k are the parameters calculated and L^*_{Fix} was the lowest value of L* measured after the slice finish its shelf life.

The experimental data and the proposed models for L* are shown in Figure 3.2. After calculating the equation parameters by linear regression and calculate the coefficients of determination (R^2) on average for the temperatures was decided that the first-order model with fractional conversion (R^2 = 0.979) was more adequate to represent the experimental information respecting the simple first-order model (R^2 = 0.976).

The change in the color coordinate a* in the sample core was modeled by using a first-order model (Eq. 3.8) and a modified enzyme kinetics equation (Eq. 3.9) based on the experimental data measured.

$$a^*(t) = a_0^* e^{-kt} \tag{3.8}$$

Where a^*_0 and k are the parameters calculated.

$$a^*(t) = a_0^* + \frac{a^*_{max}\, t}{k + t} \tag{3.9}$$

Where a^*_{max} and k are the parameters calculated and a^*_0 is the initial value of a* of the core of the slice pineapple on day 0.

The experimental data and the proposed models for a* are shown in Figure 3.3. After calculating the equation parameters by linear regression and estimating the coefficients of determination (R^2) for the different storage temperatures was decided that the first-order model (R^2_{adj} = 0.955) was more adequate to represent the experimental information than the modified enzyme kinetics equation (R^2 = 0.916) of a*.

The b* parameter evolution in the pineapple core slice was modeled by using a zero-order (Eq. 3.10) and a first-order model (Eq. 3.11) based on the experimental data.

$$b^*(t) = b_0^* + kt \tag{3.10}$$

$$b^*(t) = b_0^* e^{-kt} \tag{3.11}$$

The experimental data and the proposed models for b* are plotted in the Figure 3.4. After calculating the equation parameters linearizing the equations and checking the coefficients of determination (R^2) on average for the temperatures was decided that the first-order model (R^2 = 0.937) was more adequate to represent the experimental information than the zero-order model (R^2 = 0.936) of b*.

The color parameters of each one of the equations the temperature-influence was modeled by using the Arrhenius' law (Eq. 3.5), the parameters are presented in the Table 3.11.

According to the experimental data behavior (Figure 3.5) the core firmness change was modeled by using a power model with an initial value of F_0 (Eq. 3.3) that is the value of firmness of the fresh cut pineapple slice on day 0. A logistic model was initially evaluated but it was very far to represent the experimental data. The Figure 3.5 shows the experimental data and models for each EMAP system at each temperature including standard deviation for each value.

$$F\,(t) \;=\; F_0 - kt^n \tag{3.3}$$

In Eq. 3.3. k and n are fitting parameters for the equation adjusted respecting the experimental values by linear regression. The dependence of k on the level of O_2 was represented using a modified normal distribution equation (Eq. 3.4) where the k_{0min} is the minimum value of k on the power model presented, the parameters in Eq. 3.4 were estimated by nonlinear regression by using the damped least-squares method. The n parameter was independent of the O_2 concentration.

$$k\left(y_{O_2}\right) \;=\; k_{0min} + \frac{1}{\sigma\sqrt{2\pi}}\, e^{\frac{-\omega}{2\sigma^2}\left(\frac{1}{y_{O_2}-\mu}\right)^2} \tag{3.4}$$

In Eq. 3.4, k_{0min} is the minimum value of k and σ, μ, ω, n are fitting parameters of the equation. This approach to represent the evolution of a quality property has been used in another studies. In a study to predict quality properties of tomato fruit, the normal distribution model was used to describe the behavior of the harvest time for this fruit (Hertog, Lammertyn, Desmet, Scheerlinck, & Nicolaï, 2004). Additionally, the temperature-influence of n of the power model (Eq. 3.3) and the parameters in modified normal distribution equation (Eq. 3.4) was described by using the Arrhenius' law (Eq. 3.5). The parameters of the Arrhenius model (Eq. 3.5) for the temperature-dependent parameters in Eq. 3.3 and 3.4 are presented in Table 3.12

$$P\,(T) \;=\; P_{ref}\, e^{-\frac{E_a}{RT}} \tag{3.5}$$

In the Arrhenius model, for the temperature-dependent parameter P(T), P_{ref} corresponds to the value of reference for each parameter and E_a is the activation energy calculated by the linear regression. R is the universal constant and T is the temperature.

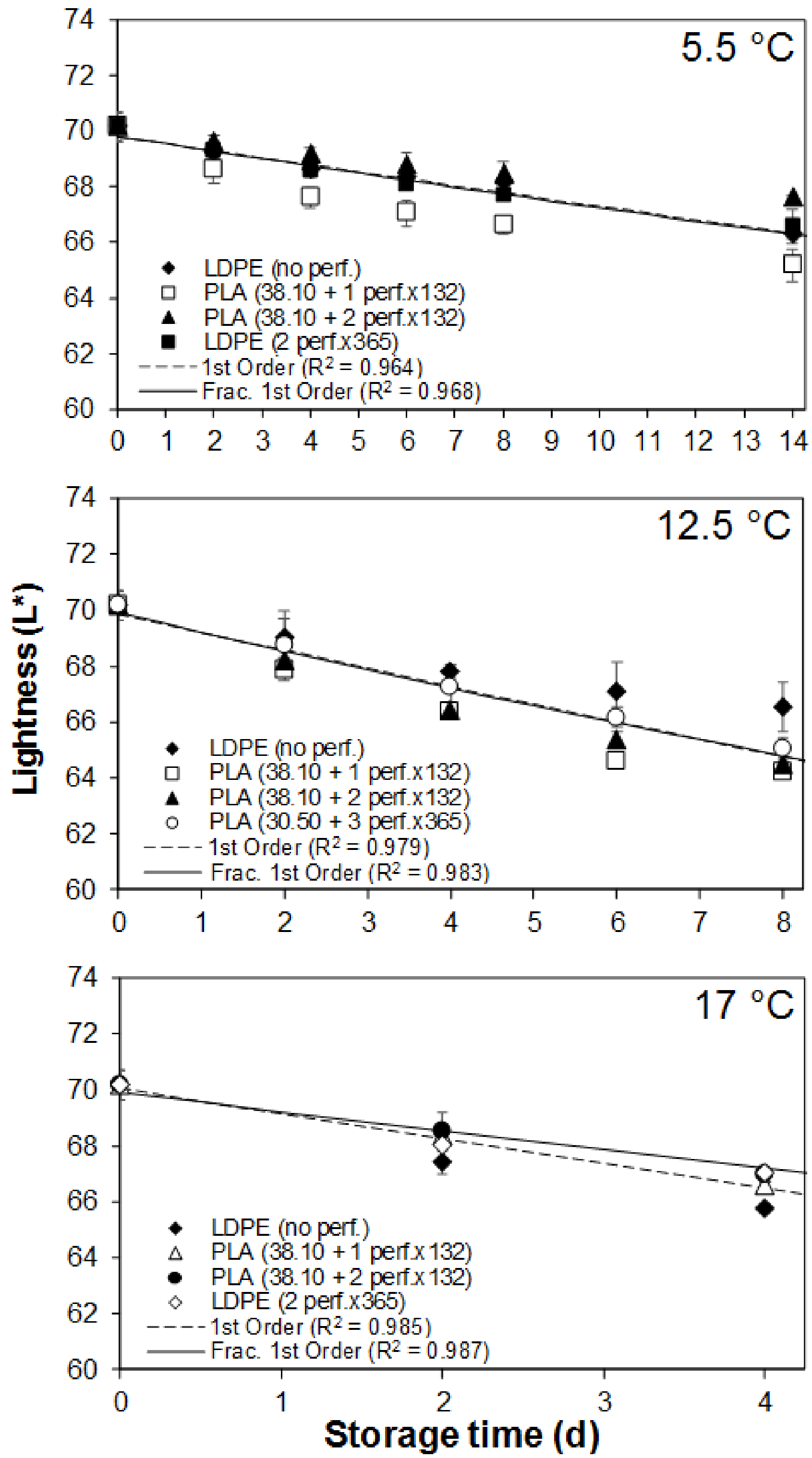

Figure 3.2. Experimental (symbols) and predicted (lines) core lightness (L*) for the pineapple slices at each one of the packaging configurations (LDPE is low density polyethylene and PLA is Polylactic acid). SD included.

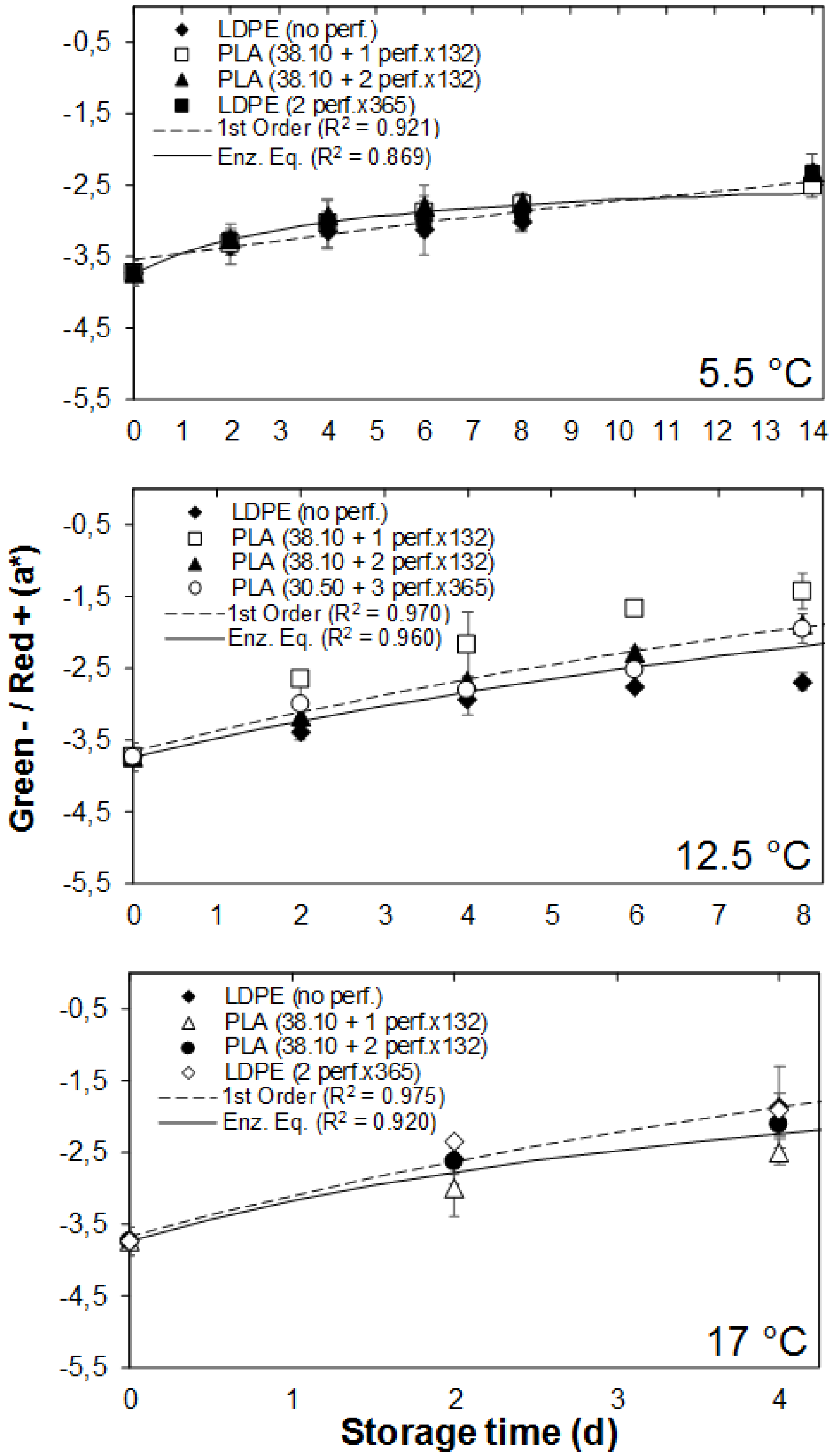

Figure 3.3. Experimental (symbols) and predicted (lines) core a* coordinate for the pineapple slices at each one of the packaging configurations (LDPE is low density polyethylene and PLA is Polylactic acid). SD included.

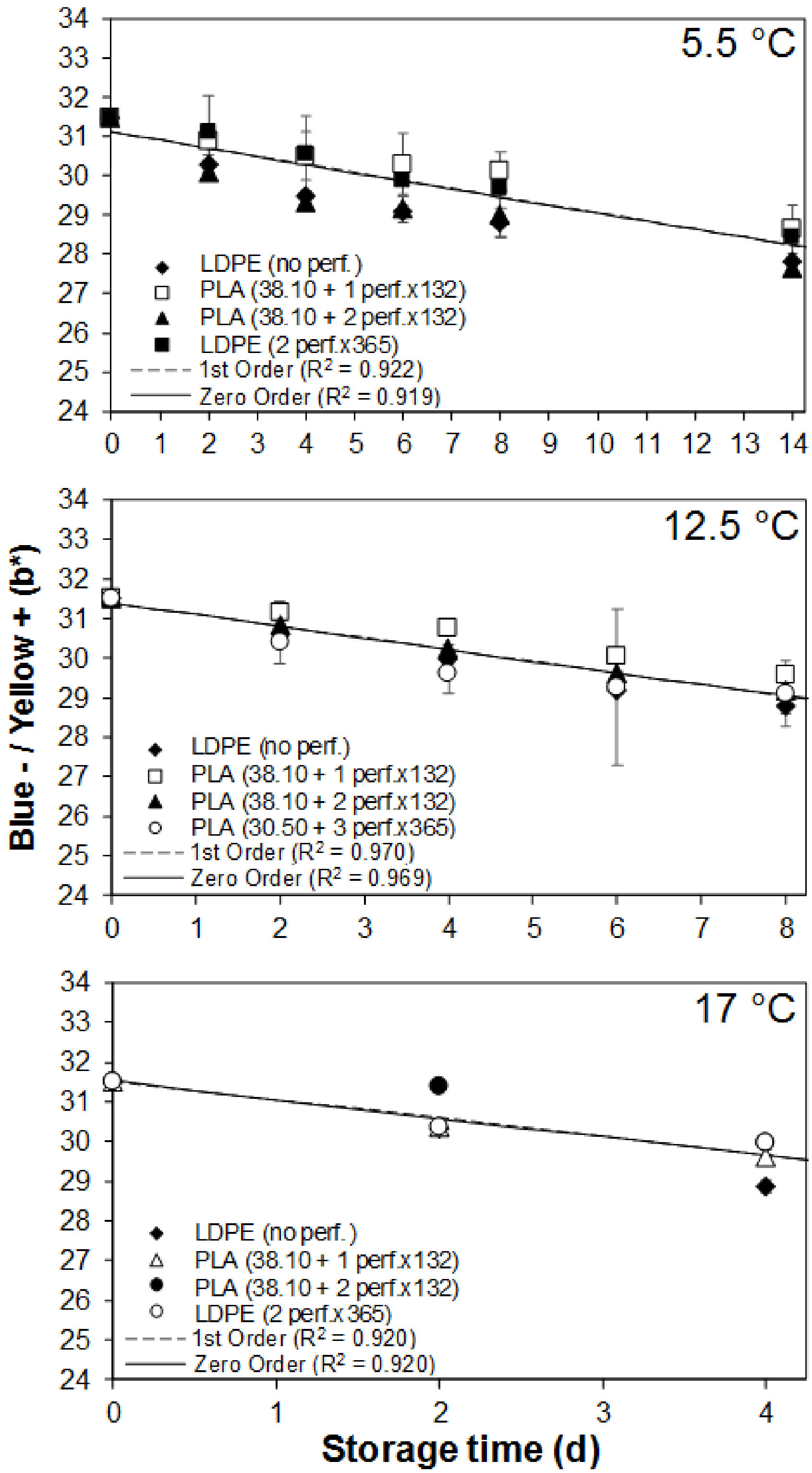

Figure 3.4. Experimental (symbols) and predicted (lines) core b* coordinate for the pineapple slices at each one of the packaging configurations (LDPE is low density polyethylene and PLA is Polylactic acid). SD included.

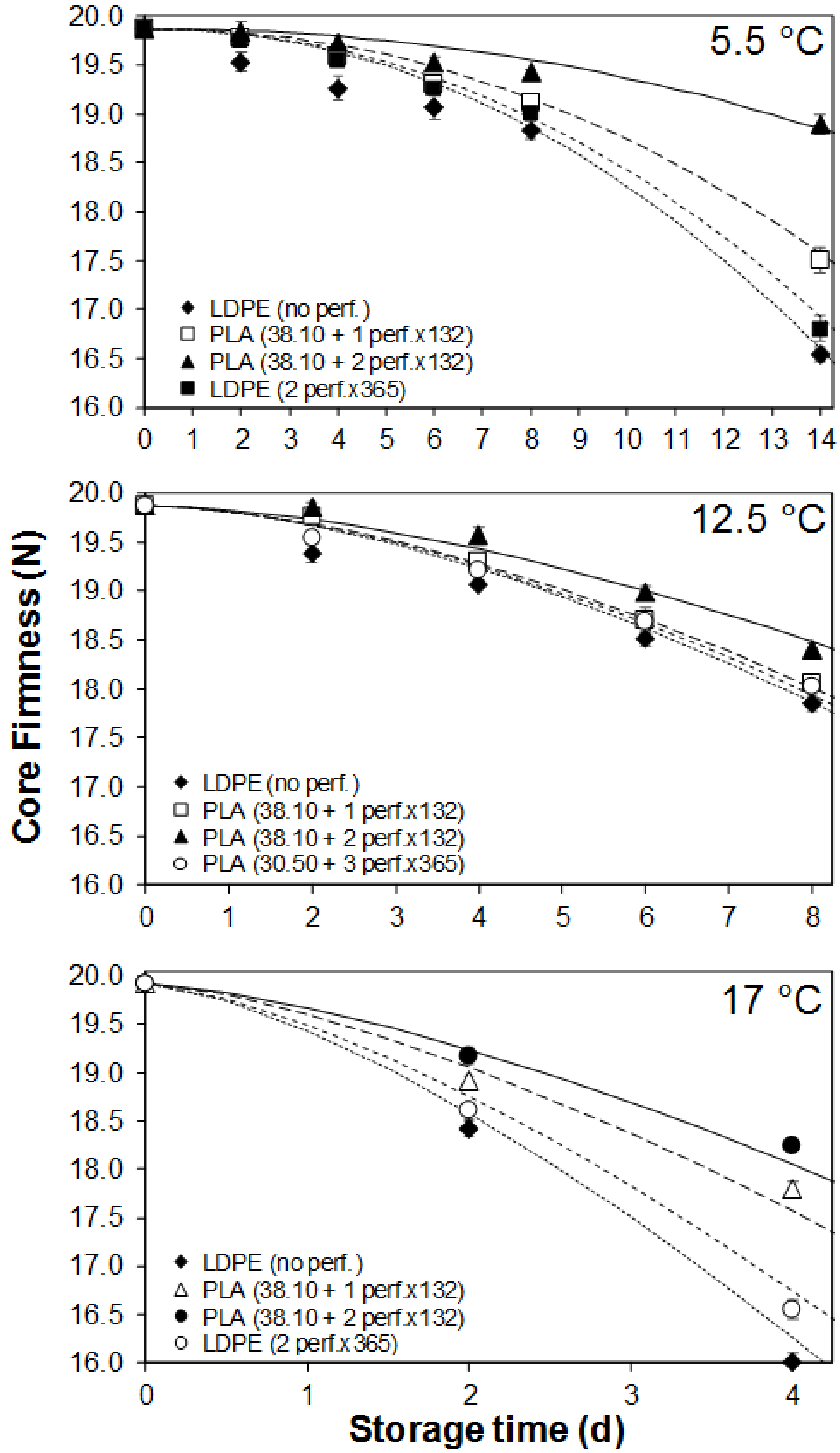

Figure 3.5. Experimental (symbols) and predicted (lines) core firmness for the pineapple slices at each one of the packaging configurations (LDPE is low density polyethylene and PLA is Polylactic acid). SD included.

Table 3.11. Parameters for the calculation of the evolution color of the minimally processed pineapple as a function of temperature and storage time.

Color coordinates (CIELAB)	**Lightness, L***		**Red/green, a***		**Yellow/blue, b***	
Temperature dependence	k	L_0*	k	a_0*	k	b_0*
P_{ref}	1.144±0.009x10^{12}	76.645±0.613	1.880±0.138x10^{17}	8.952±0.656	1.808±0.018x10^{6}	43.205±0.432
E_a (kJ mol^{-1})	74.676±0.597	0.217±0.002	100.571±7.375	2.140±0.157	44.984±0.450	0.759±0.008
R^2_{adj}	0.957	0.917	0.997	0.871	0.932	0.990

Means with different letters across each column and row are significantly different at P ≤ 0.05 by the Tukey's HSD test. Standard deviation (SD) included.

Table 3.12. Parameters for the calculation of the evolution firmness of the minimally processed pineapple as a function of O_2 concentration, temperature and storage time.

Firmness					
F_0 (N)	19.87 ± 0.03				
O_2 and CO_2 dependence					
	n				
n at 5.5 °C	2.100 ± 0.012				
n at 12.5 °C	1.650 ± 0.006				
n at 17 °C	1.450 ± 0.007				
	k_{omin}	σ	μ	ω	
k at 5.5 °C	0.0040 ± 0.00002	45.500 ± 0.259	0.1701 ± 0.001	0.5500 ± 0.003	
k at 12.5 °C	0.0045 ± 0.00002	18.175 ± 0.065	0.1381 ± 0.0005	0.1325 ± 0.0005	
k at 17 °C	0.2500 ± 0.001	1.575 ± 0.007	0.1351 ± 0.001	0.0065 ± 0.00003	
Temperature dependence	k_{omin}	σ	μ	ω	n
P_{ref}	4.643 ± 0.021 x 10^{43}	7.950 ± 0.037 x 10^{-34}	0.000387 ± 0.000	3.117 x 0.014 10^{-47}	0.000175 ± 0.000
E_a (kJ mol^{-1})	240.485 ± 1.106	-186.094 ± 0.856	-14.063 ± 0.065	-247.476 ± 1.138	-21.760 ± 0.100
R^2_{adj}	0.996	0.836	0.868	0.889	0.998

Means with different letters across each column and row are significantly different at P ≤ 0.05 by the Tukey's HSD test. Standard deviation (SD) included.

3.4.10 Modeling shelf life

The prediction of shelf life was developed in terms of the core firmness due it was the quality property that statistically showed to be significantly different when the temperature and the concentration of gases changed. The modeling of shelf life from the color was discarded because the color CIELAB coordinates only depend on the change in temperature and it is desired that a suitable shelf life model depends on both the storage temperature and the packaging configuration (i.e. concentration of gases).

From the above, the estimation of the shelf life for the minimally processed pineapple as a function of temperature and gas concentration was developed based on the data obtained for the core firmness. In the shelf life model is necessary to determine the value of the quality property corresponding with the senescence or deterioration stage. The point or time at which the product is no longer consumable. The core firmness corresponding to the senescence stage of the pineapple slices (18.75 ± 0.14 N) was determined from the experimental data based on the core firmness when the sample reach an acceptability index of 3. After determining the firmness senescence values corresponding at each EMAP, it was possible to estimate the time required to reach these values. From the Eq. 3.3. and by replacing the firmness (F) with a senescence firmness ($F_{sen.}$), the time is isolated and is converted in the shelf life time ($t_{shelf\text{-}life}$). That is the time required to reach the $F_{sen.}$ as shown in Eq. 3.12.

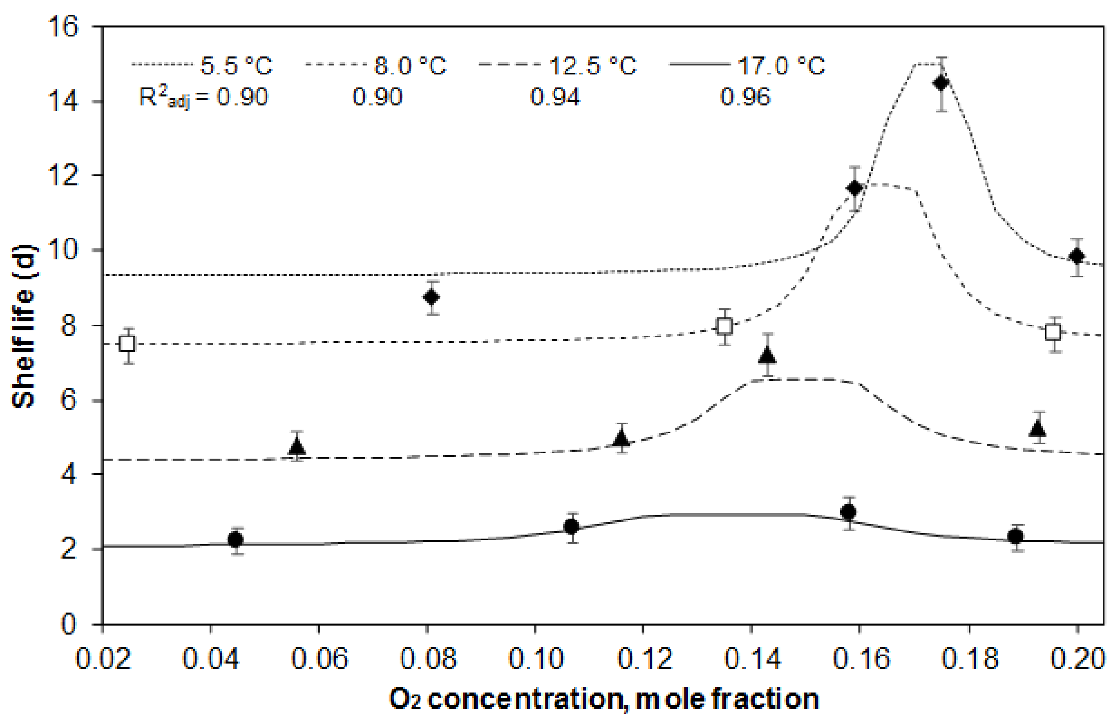

Figure 3.6. Experimental (symbols) and predicted (lines) shelf life of the minimally processed pineapple as a function of temperature and O_2 concentration. SD included.

$$t_{\text{shelf-life}} = \left(\frac{F_0 - F_{\text{sen.}}}{k}\right)^{\frac{1}{n}} \tag{3.12}$$

In the equation above, $F_{sen.}$ is the value corresponding to the senescence of the slice and $t_{shelf\text{-}life}$ is the shelf life time that can be estimated from the equation. The n and k parameters represent the same as presented in Eq. 3.3.

With the shelf life model derived from Eq. 3.3 to 3.5 and with the senescence values experimentally obtained for each EMAP, shelf life times were estimated as a function of the O_2 concentration and temperature as shown in Figure 3.6.

As can be seen the shelf lives predicted from the firmness model are close enough to the experimental data inside the standard deviation range in almost all cases. At a higher storage temperature, a shorter shelf life was measured from 2.22 ± 0.33 to 2.95 ± 0.44 days until senescence at 17 °C and from 8.72 ± 0.44 to 14.45 ± 0.72 days until senescence at 5.5 °C. As can be seen in the Figure 3.6, there is a high goodness of fit between the experimental data and the models having adjusted coefficients of determination R^2_{adj} = 0.90-0.96

Additionally, the shelf life times (white squares) corresponding with the validation temperature (8 °C) were included in Figure 3.6 being these values also satisfactory respected to the predicted ones by using the shelf life model (Eq. 3.6).

3.4.11 Validation test

For the storage test at 8 °C satisfactory results were obtained, finding that the models proposed for each quality property at each of the temperatures and O_2 concentration (firmness) can predict the experimental values with a good degree of closeness, as presented in Figure 3.7.

As evaluated at the other temperatures, the core firmness can be represented using the power law model (Eq. 3.3) and a modified normal distribution equation for the rate constant k (Eq. 3.4). The same was observed for the color coordinates with a high goodness of fit between the experimental data and the predicted values obtained with the Eq. 3.7 (L*), 3.9 (a*), 3.11 (b*) and 3.5 (Arrhenius).

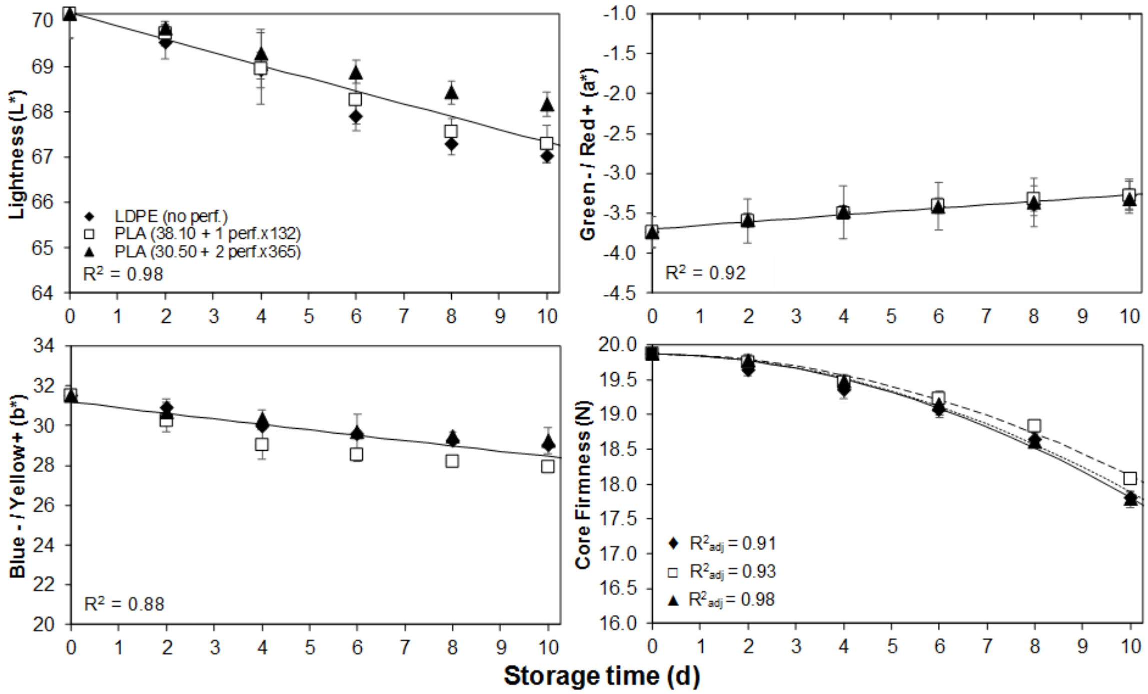

Figure 3.7. Experimental (symbols) and predicted (lines) core firmness and color for the pineapple slices in EMAP at 8 °C. SD included.

Regarding the shelf life, it can be observed that the values predicted by the shelf life model (Eq. 3.12) were satisfactory with respect to those obtained experimentally at the different gas concentrations. Therefore, the values obtained by the prediction of shelf life correspond very well with the experimental data being within one standard deviation as shown in Figure 3.7 and Table 3.13.

Table 3.13. Experimental and predicted core firmness value of senescence and shelf life time at 8 °C.

Property	$F_{sen.}$ (N) at 0.02 O_2 conc.	$F_{sen.}$ (N) at 0.13 O_2 conc.	$F_{sen.}$ (N) at 0.19 O_2 conc.
Predicted value	18.71	18.74	18.56
Experimental value	18.75 ± 0.16	18.83 ± 0.21	18.66 ± 0.12
Predicted Shelf life (d)	7.52	7.95	7.87
Experimental Shelf life (d)	7.5 ± 0.45	8.0 ± 0.48	7.8 ± 0.47

According to the results obtained from the validation, it can be evidenced that the models proposed for the prediction of texture, color and shelf life of the minimally processed pineapple are adequately adjusted to the experimental information on the proposed temperatures and concentrations of gases. Another authors have used suitable mathematical models to describe the shelf life of minimally processed fruits or vegetables (Maria L. Amodio et al., 2017; Artés-Hernández et al., 2007; Putnik et al., 2017). However, in these studies the change in shelf life or in some quality properties generally include dependence on temperature but not on other storage or packaging conditions such as gas concentrations as in this case with the inclusion of the O_2 level in the packaging headspace.

With the proposed models it is possible to establish packaging and storage conditions to create or improve the logistics of production and marketing of the minimally processed pineapple. With these it is possible to determine what will be the shelf life of the product to specific conditions of packaging and storage or accommodate the convenience of producers and distributors to obtain the information they need.

3.5 Conclusions

According to the results obtained, there is a significant relationship between the temperature and the measured values of the color coordinates L*, a* and b* and firmness for cut pineapple slices. Likewise, there is a significant effect of O_2 concentration on the firmness loss but not significant in the change of the color coordinates for the cut samples. The combination of temperature and O_2 level in the EMAP system significantly varied the deterioration rate in the cut pineapple slices. For samples packed using PLA films (38.10 µm) with 2 perforations of 132 µm at 5.5 °C (equilibrium 16.6 % of O_2 and 2.8 % of CO_2) have the lowest deterioration and decreasing in their quality properties, with a shelf life time of 14 days respecting 2 days for fruit packaged at 17 °C (1.2 % of O_2 and 9.3 % of CO_2).

Color changes of the cut slices were represented considering the effect of storage temperature by adjusting first-order kinetics and the Arrhenius equation. Firmness loss over time was represented as a function of both storage temperature and O_2 concentration in the EMAP system by using a power law equation combined with a modified normal distribution and an Arrhenius-type equation.

Since the model of firmness loss adjusted consider the effect of both temperature and O_2 concentration, this was used to derive another one to represent shelf life in the cut slices considering the firmness values corresponding with the senescence stage. The shelf life model was successfully validated with a new set of experimental data and can be used to make predictions at different conditions of temperature and packaging configuration (i.e. O_2 concentration).

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General conclusions and future research

This study was carried out with the objective of developing mathematical models to represent the change of the quality properties according to temperature and gas concentration in a MAP system for the minimally processed pineapple and use these models to find the best packaging conditions for the product and develop a shelf life equation.

In the pursuit of this objective, a review of the state of the art on minimally processed pineapple, modified atmosphere packaging (MAP) and mathematical models to represent respiration, transpiration and quality properties as a function of storage conditions was carried out. This information is presented in Chapter 1, where relevant information on how to represent respiration, transpiration and quality properties as a function of storage conditions was found.

In a MAP system the concentration of O_2 and CO_2 depends on the behavior of respiration and transpiration of the product at different storage temperatures and relative humidity. For this reason, in Chapter 2, the respiration and transpiration rates for the pineapple minimally processed in three geometric configurations were measured experimentally and modeled. Finding that experimental measurements show that higher area/weight relation, higher temperature and higher O_2 concentration leads to greater respiration and transpiration rates in the cut pineapple. In addition, was observed that extra cuts in the pineapple slices accelerated its metabolic processes. The respiration and transpiration models were adjusted satisfactorily to the data obtained experimentally and they can be used to predict these properties at different storage temperatures.

Finally, to determine the relationship between evolution of quality properties and shelf life, and packaging conditions, in Chapter 3 samples of fresh-cut pineapple were packed at three temperatures with four packing configurations for each temperature. To determine the evolution in quality and shelf life of the cut samples, an acceptability index, weight loss, firmness, color, sugar and acid content were measured on even days until the sample was discarded. Having the experimental data from the firmness and color of the fruits stored at each packaging system and storage temperature, appropriate equations were proposed to represent the experimental data by considering the shape of the curves of data. Shelf life was modeled by using the same equations and by replacing the values of firmness and color coordinates by those corresponding to the senescence stage and isolating the time, now the shelf life time, being this the response or dependent variable.

The shelf life model was successfully validated with a new set of experimental data and can be used to make predictions at different conditions of temperature and packaging configuration.

With the shelf life model developed in this study, it is possible to configure adequate packaging and storage conditions to improve the logistics of transportation and marketing of the minimally processed pineapple, because the producer can know that under certain storage conditions the shelf life of the product can be up to 14 days.

The future research of the minimally processed pineapple may be focused on the evaluation of additives and edible films that help the exposed surface of the slices to deteriorate slowly and their shelf life may increase. The use of different geometric configurations could also be proven, depending on the need, although in this study it was shown that more cuts in the fruit cause it to a respiration and transpiration increase that leads to a reduced shelf life.

Scientific Contributions

Scientific publications

Gómez, J. M., Mendoza, S. M., Herrera, A. O., Castellanos, D. A. (2019). Modeling shelf life of minimally processed pineapple (*Ananas comosus*) in modified atmosphere packaging from quality-indicative properties and storage conditions. Food Packaging and Shelf Life. In peer review.

Gómez, J. M., Castellanos, D. A., & Herrera, A. O. (2019). Modeling transpiration and respiration rate of minimally processed pineapple (*Ananas comosus*) depending on temperature, gas concentrations and geometric configuration. Chemical Engineering Transactions, 75, 547–552. DOI: 10.3303/CET1975092.

Additional publications in partnership with the 'Horticultura' research group

Sierra, N. M., Londoño, A., Gómez, J. M., Herrera, A. O., & Castellanos, D. A. (2019). Evaluation and modeling of changes in shelf life, firmness and color of 'Hass' avocado depending on storage temperature. Food Science and Technology International 25(5), 370-384. DOI: 10.1177/1082013219826825

Participation in academic and scientific events

Gomez, J. M., Castellanos, D. A., & Herrera, A. O. (2019). Modeling transpiration and respiration rate of minimally processed pineapple (*Ananas comosus*) depending on temperature, gas concentrations and geometric configuration. Oral presentation in the 2nd International Conference on Engineering Future Food. Bologna, Italy. 26 to 29 May 2019.

José Miguel Gómez Moreno

Universidad Nacional de Colombia. Bogotá, Colombia.

Modelado de la vida útil de piña (*Ananas comosus*) mínimamente procesada empacada en atmósferas modificadas a partir de propiedades indicativas de calidad y condiciones de almacenamiento.

Modeling shelf life of minimally processed pineapple (*Ananas comosus*) in modified atmosphere packaging from quality-indicative properties and storage conditions.

Tesis de investigación presentada como requisito parcial para optar al título de **Magister en Ciencia y Tecnología de Alimentos**
A thesis presented in partial fulfilment of the requirements for the Degree of Master's in Food Science and Technology

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Firma Director:

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Aníbal Orlando Herrera Arévalo

Firma Codirector:

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Diego Alberto Castellanos Espinosa